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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

SYNTHESIS 562

Repair and Maintenance of Post-Tensioned Concrete Bridges

A Synthesis of Highway Practice

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Repair and Maintenance of Post-Tensioned Concrete Bridges

A SYNTHESIS OF HIGHWAY PRACTICE

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

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The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the FHWA. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

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ABOUT THE NCHRP SYNTHESIS PROGRAM

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-05, "Synthesis of Information Related to Highway Practices," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, Synthesis of Highway Practice.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

FOREWORD

By Mariela Garcia-Colberg
Staff Officer
Transportation Research Board

The use of post-tensioning in concrete structures has allowed for the construction of economical long-span bridges. However, very limited information is available to guide bridge owners on how to maintain existing structures or, more specifically, to repair degraded post-tensioned structures. While bridge owners approach issues requiring remediation on a case-by-case basis, identification of current practices and knowledge transfer across states could improve structure integrity and reduce maintenance and repair efforts.

The purpose of this synthesis is to gather information on the practices used by bridge owners to repair and maintain post-tensioned bridges. The goal is to facilitate knowledge transfer across state DOTs, aiding bridge owners in the identification of repair practices that are working and that will extend the useful life of the bridges.

The study, prepared by Natassia Brenkus and others from the Ohio State University, captures the current practice used by bridge owners to repair and maintain post-tensioned bridges. It presents a literature review and results of a survey distributed to 50 state DOTs. Forty-five completed responses were received from the 50 state DOT survey sample, a response rate of 90%. Case examples of five DOTs' post-tensioned bridge repairs and related maintenance actions are included; these present in-depth analysis of the methods and applications, challenges, and lessons learned of each action.

The members of the topic panel are acknowledged on page iv. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

The appendix of the synthesis, which contains the survey and survey responses, is not printed here but can be found online by going to www.TRB.org and searching for "NCHRP Synthesis 562."

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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

Introduction

The use of post-tensioned concrete facilitates the construction of economical and durable structural members in bridge construction, lengthening spans and improving service behavior. Post-tensioning, a construction technique in which a precompression is applied to a concrete member, is found in many structural bridge members, such as girders, decks, pier caps, and piers. Specific aspects of this type of construction demand careful consideration throughout the structure's service life because they directly affect structural performance and durability.

Recently in the United States, repair and maintenance issues related to post-tensioned bridges have gained attention in light of instances of serious tendon degradation in structures built prior to 2000. Since the early 2000s, the industry has made significant advancements to improve the quality of post-tensioned structures, taking action to improve grout materials (including the introduction of thixotropic prebagged grouts), quality control, filler injection procedures, education of personnel, and basic details. Bridge owners have refined requirements for certification, inspection criteria, standard details, approved products, and performance. Still, agencies are addressing issues in both older and newer post-tensioned structures, and the need for continued improvement remains.

Although issues are generally approached by bridge owners on a case-by-case basis, knowledge transfer will improve post-tensioned structure integrity while reducing maintenance and repair efforts. This synthesis includes results from a survey distributed to state departments of transportation that gathered information on the practices used by bridge owners to repair and maintain post-tensioned bridges. The goal of this document is to further facilitate knowledge transfer across agencies, aiding bridge owners in the identification and implementation of successful construction, repair, and maintenance practices.

CHAPTER 1

Literature Review and Background

Post-Tensioning Basics

Post-tensioning (PT) systems are used in bridge applications in superstructure and substructure members to induce a prestressing force to the concrete section; this prestressing force causes a precompression of the concrete, which is beneficial in resisting induced tensile stress. The precompression of the concrete section—generally introduced prior to service—improves crack control, deflection behavior, and durability. Post-tensioned bridge structures are an economical construction type for spanning long distances.

PT is a form of prestressing that is accomplished after some initial curing of the main concrete section. In this method, a conduit or duct is cast into the concrete cross-section during placement of the concrete. A prestressing strand or bar is passed through the duct and anchored at each end to the concrete section. Prestressing strands are typically helically wrapped, seven-wire steel (see Figure 1). A force applied to the prestressing steel delivers the precompression to the main concrete section through the anchor points, or anchorages (see Figure 2). Prestressing strands are terminated in an anchorage (typically a steel plate) and held in place with wedge fittings. All force delivery occurs at the anchorages. The PT tendon applies both a compression force aligned with the axis of the beam and a transverse force, depending on the tendon profile. For example, angular changes of the tendon profile, created by deviator blocks or through a parabolic profile, can cause an upward or downward component of force that can be calibrated to balance structural loads.

After installation and stressing of the tendon, the space in the duct typically is filled with a cementitious material—commonly referred to as grout. Grout provides both corrosion protection to the prestressing steel and—in the case of internal tendons—bond to the primary cross-section, which is an important condition considered during design. Early post-tensioned bridge structures used mixtures of cement and water, or other nonproprietary grout mixes, as filler materials. Since the early 2000s, most agencies have shifted to specifying the use of proprietary, prebagged thixotropic cementitious grout blends (Federal Highway Administration 2013). Alternatively—although much less common in the United States than in some countries in Europe—the duct can be filled with a non-cementitious material (termed flexible filler in this document) that provides protection without bond. Several non-cementitious flexible filler materials have been used for the corrosion protection of prestressing steel in post-tensioning tendons: waxes, greases, and polymer gels (Brenkus et al. 2017b, 2018).

Internal tendons are in direct contact with the primary concrete member, while external tendons are placed outside of the cross-section of the primary member and are anchored directly at the ends. The standard practice in the United States to construct both internal and external tendons has been to use prestressing strands, sheathed or placed in plastic ducts, with cementitious

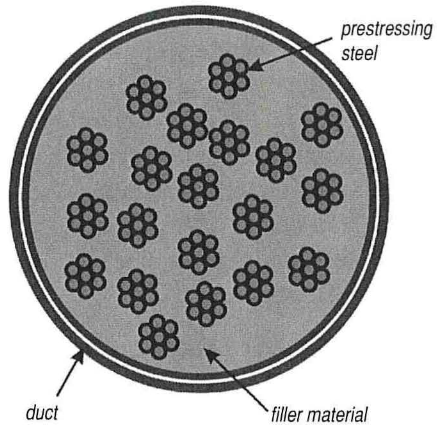


Figure 1. Typical post-tensioning tendon cross-section.

grout as a filler material. Both types of tendons may experience durability issues associated with construction practice and filler material quality; rarely have internal tendons been identified with evidence of corrosion. Lacking complete encasement in the primary concrete member, external tendons may experience an increased occurrence of durability issues.

Post-tensioning systems used in bridges are usually one of several commercially available proprietary products. A PT system is a multiple component construction composed of prestressing strands, an encompassing duct, a filler material, and an anchorage. The anchorage, which in post-tensioned systems is the location of all force transfer from the prestressing steel to the concrete, is an assembly of components: a cast or machined metal body with a bearing surface, a wedge plate, and strand wedges. In most post-tensioning applications in the United States, the utilized prestressing steel is a seven-wire, helically wrapped strand. Threaded post-tensioning bars are another commonly used option. Post-tensioning tendons are used extensively in segmental and I-girder bridges, as well as in box girders, pier caps, bridge decks, and slab bridges.

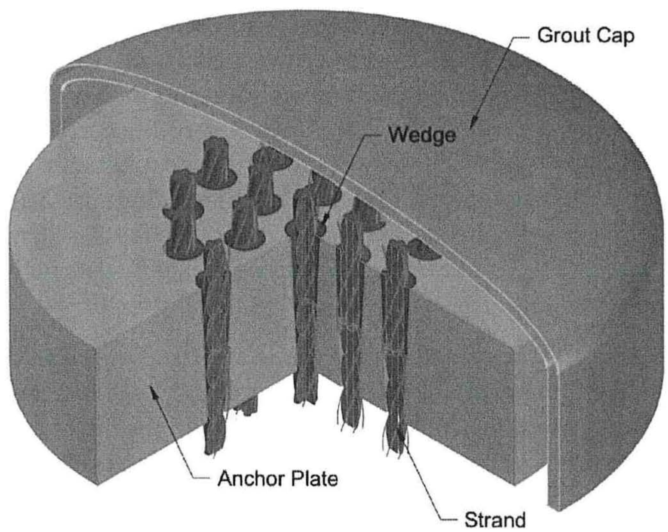


Figure 2. Typical post-tensioning multistrand anchorage.

Post-tensioning tendons can be either bonded or unbonded—a categorization based on the tendon's contact with the surrounding concrete section and indicative of stress-strain compatibility between the tendon and the surrounding concrete. Tendons filled with cementitious materials can be either bonded, as in the case of internal tendons, or unbonded, as in the case of external tendons (such as those used in some segmental construction). The use of flexible filler materials in the ducts, such as greases and microcrystalline waxes, is a recently introduced concept to bridge construction in the United States. The use of these materials results in unbonded tendons that are not bonded to the surrounding concrete section in such a way to ensure stress-strain compatibility (Brenkus et al. 2017a).

Although PT systems and components must pass acceptance testing prior to their use, rigorous studies of in-service PT systems and their specific components have been limited. Isolated cases of repair-requiring issues in PT bridges have been documented, but given the uniqueness of each situation, responses vary widely. Without a national guidance document, post-tensioning repair efforts largely rely on the expertise of the coordinating agency, consultants, and the contractors involved in the repair. This document provides a summary of current PT practices used in bridge design across the United States.

History of Post-Tensioning in the United States

Post-tensioning as a technology has been used in the United States since the 1950s, when it made its first appearance in lift-slab building construction. From its initial use to address issues with deflections and reduce member weights in lift slabs, post-tensioning expanded into other types of construction with significant technology transferred from established practices in Europe.

In 1954, the first concrete bridge using post-tensioning bars was constructed in Florida. Additional projects soon followed, with post-tensioning used to improve serviceability and lengthen spans. In 1962, the first strand post-tensioning system was introduced in the United States, an important evolution advancing the technology. The load-balancing method was popularized by T.Y. Lin starting in 1963, easing the burden of design by conceptualizing the PT tendon as "just another load." The founding of the Post-Tensioning Institute (PTI) led to many improvements in the corrosion resistance of PT systems (Bondy 2018).

Prestressing was added to the American Concrete Institute's Building Code Requirements for Structural Concrete (ACI 318) in 1963; many improvements specific to prestressing were added to ACI 318 in 1977 and 1989, including minimum requirements for bonded reinforcement, distillations of recent test findings completed at the University of Texas at Austin and the University of Washington, and greater consideration of indeterminate structures (most post-tensioned structures). Although ACI 318 is the guiding document for building design, these advancements contributed to the development of expertise and the use of PT for all structures in the United States (Bondy 2018). In 1979, two additional advancements in post-tensioning were introduced to U.S. bridges: draped tendons in girder webs and segmental structures.

Loss of prestress force is the principal concern in PT structures and can occur through several mechanisms, including thermal effects, creep, relaxation, or corrosion. Creep refers to compression-induced strain in the concrete that occurs over the life of a structure. Prestress relaxation occurs when prestressing steel experiences tensile strain over the life of the structure and loses some of its prestressing force. Creep and relaxation are critical factors in the design of PT structures because of the constant application of prestressing, but they are not fully understood for large-scale members. Excessive creep and prestress losses can lead to excessive deflections in the member and can cause cracking.

Issues are usually identified through the observation of crack formation and growth. A recent example of rapidly occurring structural degradation and "exponentially growing" cracks in a PT segmental structure is the West Seattle High-Rise Bridge. Though currently the bridge is under investigation and the cause of the cracking is unknown, the rapid crack growth observed is thought to be creating a collapse mechanism (Banks 2020). It is hypothesized that the crack growth has been accelerated by creep and thermal effects.

By far, the most significant problem facing post-tensioning has been tendon corrosion. Although significant advancements have been made to PT technology in general, corrosion remains an issue requiring careful consideration during design, detailing, construction, and maintenance. Early tendon sheathing and grease materials used in PT building construction were eventually deemed inadequate for aggressively corrosive environments; significant efforts to address these issues have led to improvements. Materials specifications and guidance documents developed by PTI for sheathing materials (including an important switch from paper wrapping to plastic conduits), strand coatings, and tendon encapsulation techniques have largely resolved early corrosion problems encountered in buildings (Bondy 2018). The concepts and the lessons learned from this construction type can, in part, translate to understanding and improvements in the bridge industry. Similar approaches—improvements in materials specifications, detailing, and comfort with the technology—have improved the finished products and durability of bridge structures in states that have invested in these efforts.

Tendon Corrosion

Tendon corrosion is regarded as the most significant problem encountered in post-tensioned structures because strand loss can compromise structural integrity and can lead to catastrophic failure (Bondy 2018). Corrosion can take many forms, including electrochemical corrosion, stress corrosion cracking (SCC), and hydrogen embrittlement.

Corrosion of concrete reinforcement most commonly occurs as an electrochemical process when corrosive agents, such as chlorides, lower the pH of the concrete surrounding the reinforcing steel and the ions react with the steel reinforcement to produce corrosion byproducts. Electrochemical corrosion can occur in PT tendons with inadequate grout, corrosion protection, or both. Electrochemical corrosion cells can form in reinforced concrete as macrocells, in which the separation between the anode and cathode is large (such as between two strands or rebar), or as microcells, in which the separation is small (such as along the same strand or rebar). Corrosion is significant because it can reduce the capacity of the reinforcing steel, as well as cause delamination of the surrounding concrete or grout. The two primary sources of chlorides are deicing chemicals and seawater (Smith and Virmani 2000).

The minimum concentration of chlorides required to initiate corrosion is referred to as the chloride threshold level. When the chloride threshold limit is reached within a concrete structure, the conditions are such that local corrosion initiation is possible (Anania, Badalà, and D'Agata 2018). A comprehensive literature review of chloride threshold values for grouted PT tendons conducted by the Federal Highway Administration summarizes historical chloride threshold values for metals in cementitious materials as reported in literature and state inspection reports (Virmani and Ghasemi 2012).

Post-tensioned structures are not necessarily more susceptible to chloride intrusion; chlorides are believed to diffuse through PT structures the same way as in other structures. However, post-tensioned concrete is more sensitive to the presence of chlorides than reinforced concrete because prestressing steel has been shown to corrode at a faster rate than mild steel. Further, the consequences of corrosion from chloride intrusion of PT structures can be catastrophic. Because PT design relies on the development and long-term maintenance of a specified prestress, the loss

of tendons, the loss of prestress due to corrosion, or the loss of both can lead to serviceability concerns (i.e., excessive deflections) or tendon failure. Extreme instances have the potential to lead to structural collapse.

Post-tensioning tendons are also vulnerable to stress-related corrosion. Because of the high stress state of PT tendons, limited corrosion can cause brittle failures in the steel due to pure stress corrosion or hydrogen embrittlement (Schupack and Suarez 1982).

The interaction between corrosion and mechanical stress can cause SCC—a brittle corrosion failure that exhibits qualities resembling fatigue failures. Prestressing steel is vulnerable to SCC because of the cold forming manufacturing process that creates its high tensile strength. The process applies stress to the steel to induce plastic deformations and modifies the material's microstructure (Toribio and Ovejero 2005). Constant prestressing force provides the stress necessary, in the presence of corrosion inflections, to initiate intergranular microcracks in the steel (Perrin et al. 2010). SCC is serious because it can cause a brittle failure—a loss of strength without evident metal loss—making it difficult to detect (Arup and Parkins 1979; Ashby and Jones 1986).

Hydrogen embrittlement often occurs in conjunction with SCC. In the low-pH environment required for corrosion, hydrogen penetrates the steel; this can have a large impact on fracture mechanics (Perrin et al. 2010). The high stress level in post-tensioning tendons is known to accelerate the steel corrosion process (Cavell and Waldron 2001; Vu, Castel, and François 2007).

Issues with PT systems in bridge structures were initially identified in 1971, when localized corrosion was identified on anchorage blocks on the old Skyway Bridge spanning the Tampa Bay in Florida. Several post-tensioned bridges have had issues with severe corrosion of the prestressing steel, with some cases of individual tendon failure. The Niles Channel Bridge in Florida started several research efforts to investigate issues with grout-related corrosion. Issues related to deficient grout and other pathways leading to corrosion (such as improperly filled vents or anchorage caps, or the use of dissimilar grouts) warrant serious investigation.

One lesson learned by the PT building industry is that significant cost savings and convenience can be had by replacing single unbonded tendons with flexible filler material, rather than replacement of entire slabs (Schwager, Schwager, and Schwager 2018). Other lessons have been learned in PT buildings as the first structures, built in the 1970s, have aged and some have required repair. These lessons may improve PT bridge performance and durability if they can be transferred from the building industry.

Grout

There are several sources of damage to post-tensioned structures—many of which are common to other types of bridge construction—including vehicle impact, environmental distress caused by saltwater or moisture exposure over time, construction error, poor maintenance practice, load-related damage, natural disaster, and extreme events (Harries, Kasan, and Aktas 2009). Specific to PT structures, issues related to the commonly used cementitious grout materials used as filler in tendons have been identified as significant contributors to damage. Grout issues include poor grout quality, poor/incomplete filling of the PT tendon with grout, contaminants in grout, and underweight bags. Grout deficiencies, such as those encountered prior to 2000, have not been completely resolved through the use of prebagged, thixotropic grouts. Also, newer grouts have demonstrated the potential for grout segregation, soft grout, excessive bleed water, and high chloride and sulfate contents (Gee 2011; Theryo, Hartt, and Paczkowski 2013).

Grout deficiencies, including their causes and remediation actions, have been investigated by several researchers and agencies. Notable research efforts have been funded by the Florida Department of Transportation (FDOT) and the Minnesota Department of Transportation.

Evidence of soft grout—unset grout with unhydrated cement products as described by Randell et al. (2015)—has been uncovered in several Florida bridges, including the Wonderwood Connector and the Mid-Bay Bridge (Hartt and Venugopalan 2002). Soft grout is generally located at the top of a duct (Randell, Aguirre, and Hamilton 2015). Work by Randell et al. (2015) suggests that grout storage conditions and the presence of inert filler materials may play a role in the formation of soft grout. The researchers also found that proprietary grouts exhibit observable sensitivity to water-to-cement ratios outside of the manufacturers' recommended value. When combined with the possibility of underweight prepackaged grout bags, this finding could have significant implications in the quality of the final product.

Several practical recommendations to reduce the occurrence of soft grout include storing grout away from water sources (to prevent unintentional cement hydration before use); ensuring the quantity of mix water reflects accurate bag weight [or test the range of mix water beyond the range recommended by the manufacturer to ensure an understanding of the materials' sensitivity (Randell, Aguirre, and Hamilton 2015)]; and carefully considering the use of inert filler materials in plain grout formulations (Hamilton et al. 2014).

Grout bleed, or bleed water, is the water that rises to the surface of grout while it is still in a plastic state. Bleed water is created when the grout's constitutive materials not used by the hydration reaction separate and settle, allowing excess water to rise toward the surface. Because PT tendons are theoretically closed systems, the bleed water is unable to escape the system. Grout bleed can become a major issue if excess water floats to the top of the grout and results in a pocket of water (or a void if the water is able to evaporate) that may lead to corrosion of PT ducts (Pielstick and Peterson 2002). The quantity of bleed water increases as the water-to-cement ratio increases, and has been observed to be influenced by wicking action.

In 2002, H. R. Hamilton conducted grout bleed testing at the FDOT Structures Research Center on four prepackaged grouts in an effort to improve agency specifications concerning post-tensioning corrosion protection. The project was initiated because of problems with an earlier generation's quality that had sparked the development and availability of new products for grouting post-tensioning ducts. This new generation of products required thorough testing before their use. The research effort investigated multiple variables, including types of cementitious grout, types of corrugated ducts, number of strands, and elevation change of the tendon profile (Alvarez and Hamilton 2002).

Revealed through field observations, bleed water prevalence in tendons with a primarily horizontal profile is distinct from its prevalence when the tendons are vertical. This difference was investigated for cementitious grout with the goal of limiting bleed water in PT tendons. To broaden specifications to address both horizontal and vertical applications, several tests were performed: wick-induced bleed tests, inclined bleed tests, and a relative fill evaluation on horizontal corrugated ducts of different types. Schupack pressure tests were conducted to examine the effect of temperature and mixing time on bleed water formation, as well as to compare grout performance.

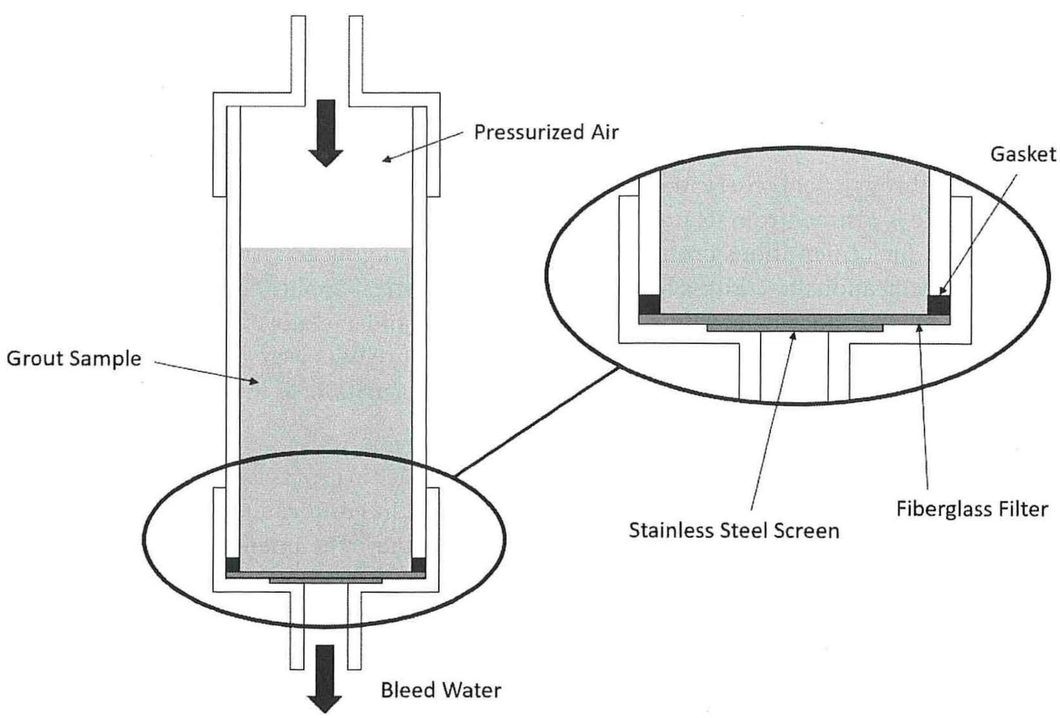
It has been demonstrated that the generation of bleed water in grouts is influenced by wicking action, or capillary action; prestressing strands embedded in grout can serve as "wicks" in the tendon, facilitating water draw from one location to another. The intent of the wick-induced bleed test is to simulate this mechanism to evaluate a grout mixture's sensitivity to wick-induced bleed. In the wick-induced bleed tests used for this study, clear, vertical polyvinyl chloride (PVC) pipes up to 25-ft tall were used to mimic post-tensioning ducts. Each vertical pipe contained either a single or a bundle of three ½-in. diameter, seven-wire prestressing strands. The setup height ranged from 10 to 25 ft with strands centered in the pipe. Grout was mixed and injected into the pipes; several grout manufacturers' products were included in the test program. Following grout injection, each pipe was visually inspected and marked, and lengths were recorded periodically for bleed water at the top and along the length of the grout column.

Schupack pressure tests are used to examine the effect of temperature and mixing time on bleed water generation. In a Schupack pressure test, the mixed grout is placed in a pressurized vessel and the pressure is incrementally increased (see Figure 3). Bleed water quantity is measured at specified intervals and is reported as a percentage of the original sample volume. Alvarez and Hamilton (2002) conducted Schupack pressure tests on four grouts, evaluating relative performance of the materials, as well as the influence of temperature and mixing time on bleed water formation.

A comparison was conducted to examine the effect of duct corrugation on the ability of the grout to completely fill the duct. Three distinct, currently available styles of ribs in corrugated duct were evaluated. The first type of duct had parallel ribs, oriented perpendicular to the running axis of the duct. The second type had spiral ribs. The third type had parallel ribs similar to the first, but with four additional longitudinal ribs that are parallel to the axis of the duct and are equally spaced radially around the circumference. Three 50-ft-long ducts, containing no strand, were filled with the same grout. Air was trapped in all three corrugation configurations (Alvarez and Hamilton 2002).

In addition to horizontal bleed testing, two inclined bleed test setups were also investigated. The inclined bleed test simulates the inclined duct conditions associated with field-observed instances of grout bleed. The setup consisted of two clear PVC pipes oriented on an approximately 30° slope. Each pipe contained a bundle of prestressing strands resting on the bottom of the pipe.

In the wick-induced and Schupack pressure tests, several conditions were shown to influence bleed water formation. Relative bleed water quantity was shown to increase with the height of the duct and number of strands. Strand bundles were also shown to generate more bleed water



Source: Adapted from Alvarez and Hamilton 2002.

Figure 3. Laboratory setup for the Schupack pressure test.

through wicking action than increased height with a single strand, suggesting that wicking action occurs between strands as well as between interstitial spaces between individual wires. Increased temperatures during mixing of the grout increased the bleed quantity in most of the tested grouts when performing the Schupack pressure test. Varying the mixing time affected the creation of bleed; most of the tested grouts developed more bleed water when mixing times were decreased. In general, it was shown that the generation of bleed in proprietary grouts was sensitive to both environmental conditions and procedural variables, and that the manufacturer's recommendations for mixing were significant to control bleed (Alvarez and Hamilton 2002).

Torres et al. (2018) performed an evaluation of shelf life of PT grout with two goals. The primary goal was to develop a test method to indirectly relate particle size growth or other cement prehydration mechanisms to the potential for soft grout development, such that PT quality could be tested for acceptance; this effort led to the creation of a modified inclined tube test (MITT). The secondary goal was to explore the sensitivity of PT grouts and their constitutive cements, supplementary cementitious materials, and admixtures to exposure conditions likely to be experienced in the field (Torres et al. 2018). The sensitivity to elevated temperature and moisture of the various constituents of PT grouts, including portland cement, supplementary cementitious materials, and powdered admixtures, was investigated.

To evaluate prehydration mechanisms of grout, a MITT was developed and performed along with a number of bench-top laboratory tests to monitor changes in material characteristics in different exposure conditions and at different ages. A MITT is useful for evaluating a grout's susceptibility to soft grout formation. In the studies to develop the MITT, several PT grouts and individual constituents were subjected to selected temperatures and humidity to simulate various exposure conditions. Four exposure conditions were assessed: (*a*) extreme exposure at 95°F and 95% relative humidity (RH), (*b*) field exposure at 85°F and 85% RH, (*c*) laboratory exposure at 65°F and 50% to 70% RH, and (*d*) control exposure at 65°F and 45% to 65% RH. Small-scale samples were tested for mass gain, particle size analysis, Blaine fineness, loss on ignition, thermogravimetric analysis, and microwave moisture content, all bench-top tests used to characterize the exposure time and conditions necessary to generate soft grout (Torres et al. 2018). All of the tested grouts exhibited physical changes, chemical changes, or both during exposure.

The primary mechanism of soft grout formation appeared to be the premature hydration of portland cement. All of the tested grouts, if given sufficient exposure time after injection into the tube, eventually formed soft grout. Field exposure resulted in an average time required to form soft grout of 8 days, with values ranging from 4 to 13 days; extreme exposure resulted in an average time-to-formation of 3 days, with values ranging from 1 to 7 days. This behavior was attributed to a combination of excess mixing water and the segregation of partially hydrated portland cement particles and low-density, low-reactivity fillers. Very fine particles of these materials were suspended in the bleed water, which was displaced as the larger particles settled due to gravity and collected in the high point of the tube (Torres et al. 2018).

Pour Backs

Pour-back details are an essential part of protecting post-tensioned concrete. Pour-back details, or "pour backs," refer to the material cast to cover the anchorage or vent assemblies of PT tendons after the filler injection process. These details serve as the "first line of defense" at key locations in the duct where access was previously required during the filler injection.

In PT bridges, there is concern that the pour-back area surrounding a tendon anchorage may be susceptible to cracking, perhaps providing a location for moisture intrusion. These regions

are often filled with a cementitious nonshrink grout to provide protection, but some agencies have reported the contractor's use of conventional concrete as pour-back material, or the complete absence of a pour back (Ahmad et al. 2018).

Few studies have focused on this particular region, despite the critical role pour backs play in protecting PT components from corrosion, especially at anchorage locations. Alvarez and Hamilton evaluated an epoxy pour-back material's susceptibility to cracking under thermal cycling. A full-scale mockup representing the end of a bridge beam was constructed with a combined anchorage zone, consisting of four anchorages covered in a single pour back of epoxy grout, and subjected to thermal cycling. Following thermal cycling tests, no cracking was noted with impact-echo results, suggesting that the bond between the epoxy and concrete remained unaffected (Alvarez and Hamilton 2002).

Historically, anchorage and vent pour backs have been problematic. A survey conducted in the early 1980s of transportation officials and post-tensioning professionals recommended better detailing for those regions because of their particular vulnerability to corrosion. Another study of an out-of-service concrete girder revealed more corrosion at PT anchorages than anywhere else in the tendon despite having been encased in concrete (Tabatabai, Ciolko, and Dickson 1995). A recent study analyzed the effects of effective prestress, clear cover depth, and chloride exposure on the rate of corrosion of PT anchorages using concrete pour backs and noted the serious consequences of anchorage corrosion (Li, Luo, and Liu 2017). Furthermore, the pour backs covering tendon vents can potentially expose the PT tendon to corrosive agents. Vents are located at the high and low points of PT tendons to allow the evacuation of air and bleed water during tendon grouting operations. Recent borescope investigations on a bridge in South Carolina revealed that insufficient grouting left voided vents, severely limiting the tendon's corrosion protection (see Chapter 3). Historically, those regions have been filled with concrete or a grout material. One of the chief concerns about the durability of pour backs is their potential for shrinkage. Shrinkage of the pour back can result in cracks that allow moisture and contaminants into the anchorage or vent. Current standard details for PT bridges often include four layers of protection for anchorage hardware: (*a*) a permanent grout cover, (*b*) a plastic grout cap cover, (*c*) epoxy grout pour back, and (*d*) for external pour backs, a waterproof coating covering the area of the pour back. Although epoxy grout is currently considered a durable material for pour backs, it can be vulnerable to shrinkage effects, allowing corrosive agents to penetrate (Ahmad et al. 2018).

Durability Issues in Florida's Post-Tensioned Bridges

The Florida Department of Transportation has encountered and handled a number of PT durability issues, including tendon failures and severe tendon degradation. As highlighted in several of the case examples, other states' bridge owners referred to Florida's experiences when faced with a PT bridge issue. Further, the FDOT's well-developed research program has funded several investigations to improve the durability of these structures. For these reasons, a specific consideration of Florida is deemed worthy of inclusion in this report.

Pre-2000

By 1999, corrosion concerns were identified in segmental bridges spanning between the Florida Keys. These corrosion concerns, and a significant number of those that followed, were linked to poor grout quality. Becoming more aware of corrosion issues, the FDOT began a concerted effort to improve PT durability. Policies and methodologies related to post-tensioning are often defined by their relationship to this key turning point. Pre-2000, filler materials used in post-tensioning systems were commonly field-blended cementitious grouts consisting of cement,

water, and expansive admixtures. Grout issues identified in the pre-2000 period were associated with

- Presence of excessive bleed water,
- Presence of voids in the filler material,
- Splitting of the encapsulating polyethylene ducts, and
- Water infiltration of the duct (water recharge).

These issues were ultimately linked to an increased potential for corrosion of the prestressing strand and, in rare cases, tendon failures. Tendon failures have catastrophic implications, negatively impacting the load-carrying capacity of the bridge. Remediation and subsequent maintenance efforts to address such events have substantial costs, both monetary and intangible.

Post-2000

Post-2000, the Florida Department of Transportation moved to implement changes to improve post-tensioning system performance and durability. Many of these changes are discussed in *New Directions for Florida: Post-Tensioned Bridges* (Corven Engineering 2004), and include the following:

- Improved PT details and hardware, including coupler improvements and anchorage protection systems
- Enhanced inspection protocols, with required training and certification of inspectors
- Required use of prebagged thixotropic grouts
- Installer training and certification requirements, including minimum experience for personnel

Industry groups made parallel moves to improve grout integrity and overall system performance. Revisions to both the PTI M50 Guide Specification for Grouted Post-Tensioning and the PTI M55 Specification for Grouting of Post-Tensioned Structures aimed to further improve grouted tendon durability (PTI 2012; PTI/ASBI 2012).

Recent Issues

Recently, the FDOT has encountered several issues in its PT structures, including segregation of the grout (sometimes visually observable as different colors in the dried grout product), contaminants (including chlorides and sulfates), soft grout, voids, and excessive bleed water. Some of these issues resulted in detrimental impacts to tendon durability. In isolated cases, tendons have failed, losing all or partial force. Tendon issues require extensive remediation actions, including—at times—tendon replacement or the addition of strengthening tendons to accommodate force loss in compromised tendons.

In recent years, additional causes for poor grout quality have been investigated, including inadequate quality assurance/quality control, improper or prolonged storage of prepackaged grout, excessive water added to the mix during the grout mixing process, insufficient mix time, uncontrolled pump pressures, grout sensitivity to extreme conditions, and mixing different brands of prepackaged grouts. Each of these contributed to further issues with grout materials used in post-tensioning systems.

In response to current grouting and tendon issues (at, for example, the Mid-Bay Bridge, Sunshine Skyway, and Wonderwood Connector, among others), the FDOT has considered a number of actions. A moratorium on all post-tensioned bridge structures was considered. Another in-depth statewide maintenance inspection was performed to evaluate the existing inventory. The current materials and practices were evaluated to identify areas for improvement. Further, the agency considered alternative PT filler materials for two reasons: to address concerns with grout materials specifically, but also to provide tendon replacement options.

Following much consideration, the agency implemented several important changes to improve PT structure durability: (*a*) adoption of flexible fillers, (*b*) use of diabolo-shaped voids at diaphragms and deviator blocks, and (*c*) detailing to accommodate full tendon replacement (Robertson 2014).

Two characteristics of flexible filler are viewed as advantageous: flexible filler provides corrosion protection, and tendons utilizing flexible filler can be detailed to allow future tendon removal and replacement, facilitating later maintenance and repair of the tendon, if necessary. The agency's motivations are reflected in its current guidance: "Design and detail all tendons that utilize flexible filler to be unbonded, fully replaceable, meet anchorage clearance requirements . . . and have clearance at the anchorages for jacking and future tendon replacement operations" (FDOT 2020).

Current FDOT specifications only allow microcrystalline flexible filler materials that are heated to facilitate their injection, though other "flexible" fillers exist, such as thixotropic gels (that can be pumped without applied heat). The FDOT-approved products are stable, non-separating products, with good adhesive qualities, which are semisolid at typical ambient temperatures in Florida (reducing opportunities for leakage).

In 2016, additional criteria and guidance were added to the FDOT specification to clarify requirements for post-tensioning system approval for use with flexible filler. Post-tensioning tendon systems are evaluated and approved through a battery of tests to ensure optimal performance characteristics; characteristics and tests performed are different from those conducted to approve PT systems for grout use. The majority of the test requirements are modeled off fib Bulletin 75, the European guidance document for technical approval of polymer (plastic) post-tensioning ducts. In general, the prescribed tests ensure that PT components (duct and duct couplers) demonstrate

1. Sufficient longitudinal load resistance,
2. Leak tightness,
3. Flexibility of the duct system, and
4. Integrity of the duct couplers.

   Duct couplers, in particular, are of concern because these connections are sometimes made with "heat-shrink" materials, with implicit heat sensitivity that may be detrimental during injection of heated filler materials.

PT system assemblies, which are tested with all components from anchorage to anchorage, are also required to demonstrate

1. Leak tightness of the anchorage-duct assembly,
2. Full-scale duct system assembly, and
3. Leak tightness of the assembled duct system.

   These requirements are intended to ensure that the PT system, if properly assembled, will remain intact from the time of initial installation to the injection.

History of Flexible Filler Use

In 2014, the Florida Department of Transportation adopted the use of flexible filler materials as alternatives to the commonly used cementitious grouts (Robertson 2014). Specific tendon types were identified for which flexible filler would be used. The agency also required that tendon detailing accommodate future tendon replacement; a specific detailing change to facilitate tendon replacement was the requirement of the use of diabolo-type voids at deviation points. These changes were introduced as a means of improving PT durability in light of FDOT's experience with PT issues (Brenkus et al. 2017b). At least one other state (Virginia) has used flexible filler in PT tendons (in the Varina-Enon Bridge).

Flexible filler materials are not new. Since World War I, flexible filler products have been used for corrosion protection of naval machinery and coastal artillery. In addition, they have been used by several industries; in the nuclear industry, they have been used in PT tendons in nuclear containment structures. The materials have been used by the U.S. nuclear industry since 1969 (Bhatia et al. 2017; Brenkus et al. 2017b).

Applications Targeted for Flexible Filler in Florida

The specification of flexible filler materials in FDOT projects is informed by the agency's past experience with grout issues. The tendon profiles targeted for flexible filler are those profiles with demonstrated past evidence of increased incidence of grout issues, or those tendons that, if lost, would cause severe consequences to the structure. Tendons with significant profile drape, for example, have been identified by the agency to have exhibited more grout issues. In addition, particularly long tendons, and PT tendons made of strands (instead of bar), are more susceptible to grout issues and, therefore, require flexible filler.

Flexible filler materials are now required for all external strand tendons and all continuity strand tendons. Some applications permit the use of either flexible filler or grout, including in straight strand or parallel wire tendons—other than continuity tendons in U-beams and girders—and in bar tendons such as those found in vertical or horizontal orientation in a bridge substructure or superstructure.

Some applications still require the use of grout filler material. In Florida, grout fillers are still required for transverse top slab tendons. There is concern that a reduced cross-section in the top slab—by creating "voids" at the duct locations, as would occur if flexible filler were used—would lead to cracking or susceptibilities in the deck. A solid, rigid filler is preferred in these locations to transfer the live load to the main structure. At this time, all tendons adjacent to the riding surface are filled with grout filler materials, including top slab cantilever or transverse tendons in segmental box girders. Further, tendons with a profile drape of 2 ft or less in slab-type superstructures are also required to include bonded, grout-filled tendons. Post-tensioning systems using bars are also permitted to use grout as the filler material because these systems have not demonstrated the same corrosion concerns as strand tendons.

Current Practices and Lessons Learned

As a preemptive measure to improve PT tendon quality, FDOT requires contractors perform full-scale tendon mockup injections to demonstrate a successful injection procedure plan on the planned tendon profiles. This requirement ensures that the proposed post-tensioning system, filler material, equipment, and injection method can fill the tendon ducts fully. Mockup injections provide an opportunity for contractors and injection personnel to identify both preferred practices and potential issues prior to the actual injection, minimizing issues at the jobsite. Further, these injections are advantageous because they add to the body of knowledge regarding the use of flexible filler, including identifying lessons learned and improving future specification revisions and contractor practices.

FDOT identified practices and lessons learned during the recent construction of the first structures to use flexible fillers. These practices are in addition to the formalized guidance included in the FDOT specifications (FDOT's Structures Design Guidelines 2020).

The following are current practices and lessons learned:

- Worker safety protection (such as gloves, Tyvek protection, face shields) is required for heated materials.
- Duct coupler/connections should not be located in a curved region of the duct.
- Pre-bending of the high-density polyethylene (HDPE) duct for placement in curved regions may facilitate its placement.

- To facilitate remediation during flexible filler injection, it is useful to have the following on hand:
  - Buckets with water and wet rags to cover small leaks
  - Heat gun or torch to address clogs in plumbing
  - Clean-up supplies, such as sand and shovels, in case of flexible filler spillage
  - Tarp or other covering for areas adjacent to the inlet and outlet points (to keep these areas clean in case of material leaking)
  - Barrier or other protection at key areas in case of blowout
- Ensure that all components of the pumping system are clear prior to injection, including plumbing on the pump and between filler reservoirs. All hoses should be cleaned and cleared immediately before injection. Clogs in hoses, if not cleared, can be transferred from equipment into the tendon and can lead to void formation. If using multiple barrels in parallel, ensure that all components of the pumping system are included in the recirculation procedure to prevent clogs.
- Regarding pumping pressure increases: Like with grouted tendons, pressure spikes during injection are more likely in internal tendons than in external tendons because of the confinement provided by the encasing concrete.
- Incidence of tendon crossover can be minimized by vacuum and pressure tests prior to the injection.

Design Strategy

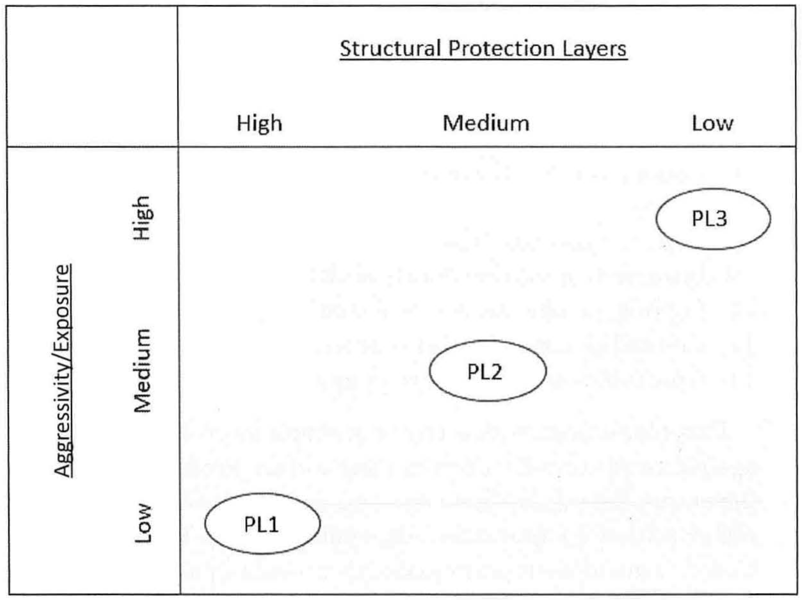
The International Federation for Structural Concrete (fib) suggests a tiered approach to strategize the design of the PT system's corrosion protection. The guidelines outlined in the *fib Bulletin* are the same as those presented in the PTI M50 Guide Specification for Grouted Post-Tensioning (PTI/ASBI 2012). A structure is designed with a designated protection level (PL), which guides design decision making of protective elements. The PL is selected on the basis of the exposure of the structure and the aggressiveness of the structure's environment (see Figure 4). Alternatively, the PL may be selected, in part, on the basis of the post-tensioning system's potential exposure to corrosion-inducing chlorides (see Figure 4).

PL-1 is designated for post-tensioning systems in mild environments with a high level of protection afforded by the structural components (see Table 1). PL-1 is the minimum protection that should be provided for a post-tensioning system. Ducts in PT systems at this level can be made of either corrugated metal or plastic, but they must be completely filled with a filler material, leaving no voids. PL-1 is further delineated into PL-1A, and PL-1B. PL-2 encompasses the same design and detailing protection measures as PL-1, but the ducts must be plastic and watertight and have specific testing done to ensure airtightness. PL-3 is for the most aggressive environments, such as those encountered in marine environments or in locations where deicing salts may contact the structure. PL-3 encompasses the same considerations as PL-2, but implies the use of monitorable, electrically isolated tendons for additional protection.

Post-Tensioning Durability

Post-tensioned bridges are efficient in spanning long distances. When properly designed and constructed, these systems offer a durable design solution for longer bridge spans.

Durability is an imprecisely defined characteristic in the field of structural engineering. In general, it is understood to mean the long-term performance of the structure during its intended design life, including its resistance to environmentally influenced degradative forces. Though occurring rarely, damage to PT systems can have significant implications. Corrosion of a post-tensioning tendon, for example, can result in a loss of structure integrity, reduction in structural safety, and the need for costly repairs such as tendon replacement.



Source: Fuzier et al. 2005.

Figure 4. Recommended protection levels on the basis of environment.

Table 1. Protection levels according to PTI M50.

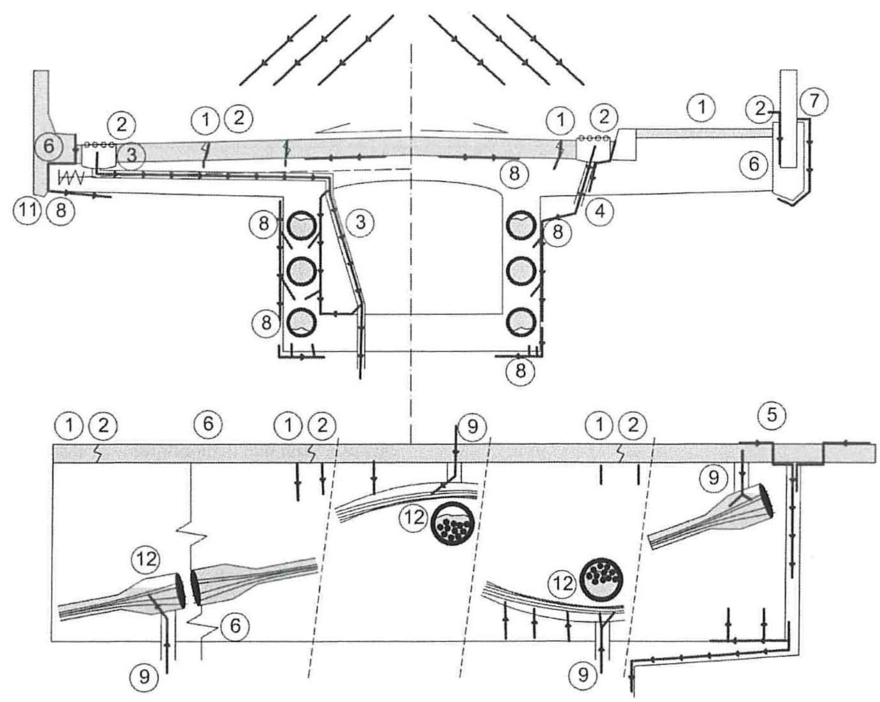
Protection Level	Aggressiveness of Environment	Basic Requirements
PL-1A	Low	Basic grout or engineered grout; nonreactive filling material; grout filling leaving no voids
PL-1B	Low	PL-1A measures, plus engineered grout and permanent grout cap
PL-2	Medium	PL-1B measures, plus an envelope providing a permanent leak-tight barrier
PL-3	High	PL-2 measures, plus electrical isolation of tendon or encapsulation that is monitorable or inspectable at any time

Protection of PT Systems

In general, ensuring durability for PT systems is related to the protection of the system against water intrusion. Bulletin 33, the fib guidance for improving durability of PT systems, identifies potential sources of durability concerns and breaks them down into two categories: failure of the external barriers, and failure of the tendon corrosion protection system. Identified pathways of water intrusion (which could carry detrimental chlorides) include the following (note that the numbers in the following list correspond to those in Figure 5):

1. Defective wearing course
2. Defective waterproofing membrane
3. Defective drainage/pipes
4. Incorrectly placed or defective outlets (reducing drainage)
5. Leaking expansion joints
6. Leaking construction joints
7. Inserts
8. Defective concrete cover
9. Incorrectly filled vents/inlets/outlets
10. Leaking metallic ducts (not shown)
11. Cracked or porous pocket concrete
12. Grout voids at high and low points

Post-tensioning systems rely on multiple layers of defense to protect the prestressing strand against moisture and corrosion mechanisms. Protection is afforded by the structural concrete, the encapsulating duct material, and the filler material. Filler materials provide different corrosion protection approaches, depending on their type. More than simply serving as a physical barrier, cementitious grout materials provide a passivating layer. Flexible filler materials such as petroleum-derived waxes provide corrosion protection through their inherent hydrophobic



Source: fib Bulletin 33.

Figure 5. PT system vulnerability.

nature. They may also be formulated with corrosion-inhibitor additives to further facilitate resistance to mechanisms of corrosion.

Corrosion Protection of PT Anchorages

PT anchorages are the most critical part of the PT tendon because they are the locations at which all prestressing force is transferred to the concrete member. Four levels of corrosion protection are provided at post-tensioning anchorages to guard against corrosion at these locations. Tendon filler material, which may be either a cementitious grout or a flexible filler material, provides a first level of corrosion protection. A second level of protection is provided by the anchorage cap, occasionally called a grout cap, which remains in place when the structure is in service. A third level of protection depends on the construction type: for tendons terminated at an exterior surface, protection is provided by a pour back, or for tendons internal to the main concrete cross-section, such as those in a segmental box girder, protection is provided by the concrete section. Finally, a seal coat provides a fourth level of protection.

Industry Standards and Certification Programs

Notable improvements have been made over the years as the post-tensioning industry has matured. Several industry groups are engaged in educating and promoting the use of post-tensioning in some form, including the Post-Tensioning Institute, the American Segmental Bridge Institute, the Precast/Prestressed Concrete Institute, and the American Concrete Institute. Although post-tensioning is not necessarily the primary, specific interest of some of these organizations, all of them are engaged in developing consensus-driven guidance that ultimately benefits the PT industry.

The PTI M50 and M55 documents are frequently referenced by state departments of transportation (DOTs) in their specifications for post-tensioned structures (see survey, Chapter 2). PTI/ASBI M50.3 Specification for Multistrand and Grouted PT, a consensus specification with stakeholders from the owners (DOTs), bridge designers, PT system suppliers, component manufacturers, and academia, requires the following personnel qualifications:

> "**7.1 — Supervision**
>
> Post-tensioning operations:
>
> - The Direct Supervisor of Post-Tensioning Operations shall be certified as PTI Level 2 Multistrand and Grouted PT Field Specialist;
> - The Foreman of each installation and stressing crew shall be certified as PTI Level 2 Multistrand and Grouted PT Field Specialist;
> - The Foreman of each grouting crew shall be certified as PTI Level 2 Multistrand and Grouted PT Field Specialist and ASBI Certified Grouting Technician; and
> - At least 25% of each crew shall be certified in PTI Level 1 Multistrand and Grouted PT Installation."

The PTI M55.1 Specification for Grouting of Post-Tensioning Structures, also a consensus document with the same stakeholders, outlines requirements for grout materials and grouting procedures. Both the M50.3 and M55.1 specifications are to be used together for bonded post-tensioning.

Important improvements to the end-product quality and durability of PT structures are, in part, attributable to the development and increasing use of certification programs. Certification programs are aimed at training, educating, and standardizing industry expectations to improve the quality of PT concrete structures by certifying field personnel, inspectors, tendon fabricating plants (more applicable to the building industry), and plants producing prestressing steel. Some states require the personnel to have attained such certifications to work on their PT projects,

while other states (such as Florida) go a step further and have their own Construction Training and Qualification Program in conjunction with recognized certification programs. Certification programs offered by PTI and ASBI serve to educate and train personnel engaged in PT construction. Certification renewal for both PTI and ASBI is required periodically (every 4 years and 5 years, respectively).

Field personnel certification programs relevant to bridge and infrastructure projects offered by PTI include separate specialist and inspector programs. PTI offers Level 1 and 2 Multistrand and Grouted PT Specialist programs—workshops aimed at educating personnel engaged in the installation of multistrand and bar PT systems. These programs cover aspects related to installation procedure, as well as safety concerns, grout materials, and grouting techniques of multistrand applications. Level 1 certification is attainable without any prior fieldwork experience; Level 2 certification requires a minimum of 1,500 hours of relevant fieldwork experience (of which 250 hours are required in each of the following: installation, stressing, and grouting, or inspecting these operations).

The PTI Level 1 and 2 Multistrand and Grouted PT Inspector program is a workshop designed to certify inspectors involved in the inspection of multistrand and bonded post-tensioning systems in multistrand applications, such as bridge infrastructure. This program assumes familiarity with post-tensioned multistrand applications, reflected in the requirements for participation in the program. A prerequisite for participation in the Level 1 or the Level 2 inspector certification is either current certification as a Level 1 Multistrand and Grouted PT Installer, or as a Level 2 Multistrand and Grouted PT Specialist. Fieldwork experience is not required to achieve Level 1 inspector certification. To achieve certification as a Level 2 inspector, the participant must have 500 hours of relevant experience in inspection of PT systems (of which 100 hours are required in each of installation, stressing, and grouting inspection).

The American Segmental Bridge Institute offers personnel certification through its ASBI Grouting Certification Program to provide supervisors and inspectors of grouting operations with appropriate training. The ASBI Grouting Certificate can be attained by participation in the training; certification as an ASBI Certified Grouting Technician requires both workshop participation and 3 years of experience in the construction of grouted post-tensioned structures.

Since 2017, ASBI and PTI have jointly worked with the Florida Department of Transportation to provide the Flexible Filler Certification Training program, offered annually, to educate personnel, contractors, designers, and inspectors on aspects specific to the use of flexible filler materials in post-tensioned bridge projects. The training includes instruction in the unique injection process; material characteristics of flexible filler; required equipment; and relevant FDOT policies, specifications, and design standards. FDOT currently requires construction and inspection personnel working with flexible filler to have this certification.

Industry groups also have published key guidance documents. Two frequently referenced documents are the PTI/ASBI M50 Guide Specification for Grouted Post-Tensioning and PTI M55 Specification for Grouting of Post-Tensioned Structures.

The PTI/ASBI M50 Guide Specification for Grouted Post-Tensioning is a guidance and specification document for post-tensioning applications in buildings, bridges, storage vessels, and other structures, except stay-cable structures and rock anchors. It was first published in 2012 and is a joint effort of the Post-Tensioning Institute and the American Segmental Bridge Institute. The document provides general guidance for post-tensioning *systems*, including their handling, installation, stressing, grouting, and protection. It also sets minimum standards for post-tensioning work and components, defines testing requirements to qualify PT systems, and provides guidance on performance (or protection) level selection by the designer. It applies to buildings, bridges, storage structures, and other structures using grouted post-tensioning tendons, excluding

stay cables and rock anchors that are already covered by other PTI documents. The protection levels outlined in the M50 guide are the same as those found in *fib Bulletin* 33 (PTI/ASBI 2012).

The PTI M55 Specification for Grouting of Post-Tensioned Structures is a separate guidance and specification document that outlines current practices specific to cementitious grout filler materials and their use in post-tensioned structures. It was first published in 2003 and is in its third edition. It provides minimum requirements for selection and design, injection of grout, and installation of ducts in post-tensioned systems. The document is focused on ensuring "essentially complete filling of the duct": materials, design, quality assurance and control, equipment, and construction. The M55 document limits its scope to PT systems with steel prestressing elements and cementitious grout filler materials and does not address vacuum grouting. It also provides some troubleshooting for grouting problems (PTI 2012).

Inspection

Inspections of in-service post-tensioned bridges, like other bridge structures, are subject to the National Bridge Inspection Standards (NBIS) requirements for inspection (FHWA 2020). NBIS requires inspection of all publicly owned highway bridges greater than 20 ft in length. In most cases, routine inspections are required every 24 months and consist of visual observations. For bridges with known deficiencies, inspection frequency is stipulated to occur more often. In addition to NBIS, FHWA has mandated that element-level condition ratings (based on the *AASHTO Manual for Bridge Element Inspection*) be submitted for all bridges on the National Highway System. Also, some states have their own inspection requirements, often with requirements for increasing frequency and complexity if issues arise. Inspection requirements specific to PT structures are not explicitly described by NBIS; at least one state (Minnesota) has published research efforts to improve inspection practices and remedial grouting contracts specific to PT structures (Chauvin 2017; Schokker and Berg 2012).

Most agencies employ inspectors with general bridge expertise that may or may not include PT bridge experience. As some of the case examples illustrate, developing issues in PT structures may not be caught in regular inspection.

Visual inspection is the primary means of assessing the condition of a bridge, including post-tensioned bridges. Such inspections are usually conducted on a periodic basis, with frequency dependent on the agency and documented history of the structure. Inspections conducted after a rainfall event (*fib Bulletin* 33) may provide particular insight into potential damage or areas of concern in a system, including the potential of water flow through the structure. Several agencies (Virginia DOT, South Carolina DOT) have documented water penetration occurring during or shortly after rainfall events.

Inspection of post-tensioning systems requires a detailed, thoroughly considered approach because issues with or damage to post-tensioning systems are not always immediately evident. Damage to PT systems, at the same time, can have significant implications; corrosion of a post-tensioning tendon can result in a loss of structure integrity, a reduction in structure safety, and the need for costly repairs, such as tendon replacement.

Inspections of PT systems are conducted to identify and gather information on the following (but are not limited to): cracking, discoloration, joint leakage, spalling and delamination, water flow or other evidence of moisture, honeycombing, rust staining, and duct damage. Inspection methods for post-tensioned bridge systems vary in complexity and impact to the structure; inspection methods are chosen by agencies on the basis of evidence of potential concern or issues. In general, visual methods are relied on for routine inspections. Inspection approaches requiring invasive or destructive methods are not a first action and are usually specified only if the owner has reason to suspect the PT system has been compromised.

Project-specific detailing, construction errors, and material selection can affect the ease of inspection. Internal post-tensioning tendons—and especially grout-filled post-tensioning tendons—pose a difficulty for inspectors. In cases in which these types of tendons require repair or replacement, these tendons are particularly difficult to address because of their bond with the main concrete member. In other cases, access for inspection has unintentionally been blocked during construction; for example, the Varina-Enon Bridge in Virginia lost access to its PT columns when concrete was poured over access holes (see Chapter 3).

Guidance for inspecting and restoring tendons with defective grout has been published by FHWA (Theryo, Hartt, and Paczkowski 2013). This document guides state departments of transportation in their inspection of grouts used in post-tensioned structures, including the post-2000 prepackaged, thixotropic grouts that have been the subject of only limited study.

Nondestructive Evaluation for Post-Tensioning

Nondestructive evaluation (NDE) techniques can be used for the inspection of post-tensioning systems. Many different technologies exist for aiding PT system inspection, including many proprietary systems. Each NDE technology has its own unique efficacy and limitations; no NDE approach is universally capable of inspecting all aspects and all types of the variety of post-tensioning systems present in PT bridges. Various techniques have been developed and numerous efforts have been made for defect detection (for example, strand breakage) and for monitoring prestress levels in both bonded and unbonded post-tensioning tendons. Some of those techniques include the following:

- Ground penetration radar
- Radiography
- Global dynamic approach
- Magnetic flux leakage
- Magnetic permeability
- Magnetostrictive sensing
- Electrochemical methods
- Electromechanical impedance-based technique
- Time-domain reflectometry
- Impact-echo method
- Pulse-echo technique (ultrasonic testing)
- Guided wave ultrasonic technique
- Acoustic emission technique

Several factors influence the performance of NDE techniques, including elements of the post-tensioning system (such as the duct material and filler material), the geometry of the main structural element (geometry of the member), and even the type of defect or damage. In general, a combination of NDE techniques is required to adequately assess the condition of a post-tensioned system (Azizinamini and Gull 2012).

These techniques can be broadly categorized into five classes of noninvasive NDE techniques: electrochemical methods, electromagnetic methods, mechanical wave or vibration methods, radiological methods, and magnetic methods. In addition, options for invasive, low-destructive evaluation (LDE) exist. Efforts to develop and implement these approaches have produced mixed results and levels of success. Many are not suitable for in-situ applications because of various limitations, such as susceptibility to environmental changes, high scattering of data, and insensitivity to relatively small defects. However, a few of them show promise and have several advantages over the other methods. A brief overview of the most common types follows.

Electrochemical Methods

Electrochemical methods are inexpensive methods used to monitor active corrosion of strands in concrete structures by measuring the electrical properties of the reinforcing steel. Most electrochemical techniques use the same measurement setup that consists of a reference electrode, a working electrode, a counter electrode, and a voltmeter. A closed electrical circuit is required, so direct electrical connection to the inspected steel strands must be established, as shown in Figure 6. To create this direct connection, sensors must be placed inside the duct, which poses a problem for monitoring existing PT ducts that do not have those sensors.

Another major limitation of electrochemical methods is that these techniques do not measure corrosion activity in voided areas. This limitation is significant because several of the identified strand/wire breaks in post-tensioned structures have occurred at void locations, as seen in the Varina-Enon Bridge (see Chapter 3, Case 4).

Four different types of electrochemical techniques have been developed, including half-cell potential, linear polarization resistance (LPR), electrochemical impedance spectroscopy (EIS), and electrochemical noise. The half-cell potential measurement is a technique widely used to evaluate active corrosion in reinforced steel and prestressed concrete structures. The half-cell potential is a quick measurement that is taken by using a voltmeter to find the potential difference between a reference electrode and steel reinforcement. This method is less reliable for prestressing steels and large concrete covers, and for concrete with certain constituents that inhibit voltage potential. Alternatively, LPR determines the instantaneous corrosion rate in metal. In LPR, steel is slightly perturbed electrically from its equilibrium potential. Once the electrical potential is changed by a known amount, the current decay is tracked and related to the condition of the reinforced concrete structures. These measurements can then be compared with the measurements of the EIS tests. EIS uses a small amount of alternating current with a particular frequency applied to a metal electrolyte interface to calculate the impedance of the interface between steel and concrete. Impedance is calculated for various frequencies to find values of parameters that can be used to fit the measured data. Finally, the electrochemical noise technique monitors fluctuations in open circuit potential and current to infer how the system corrodes and it is mainly used to detect pitting corrosion.

Of the four mentioned techniques, half-cell potential and LPR are the most commercially accessible. The former gives information on the probability of corrosion and the latter is related

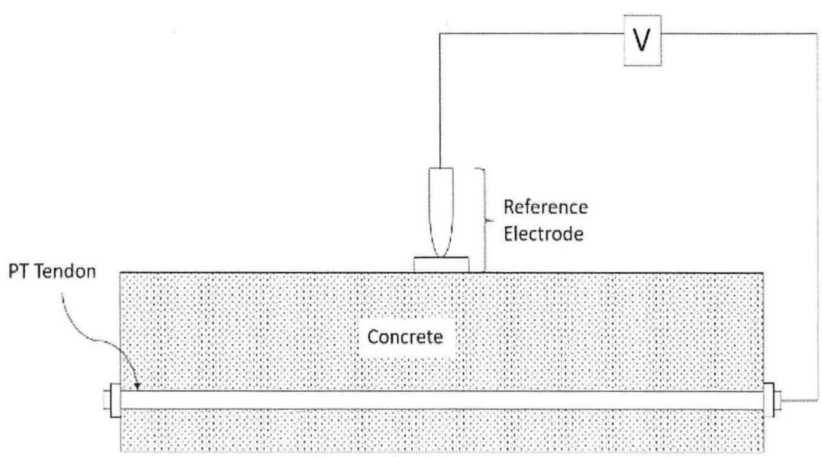


Figure 6. Fundamental measurement setup for electrochemical techniques.

to the corrosion rate. The half-cell potential method is practically and widely employed to identify the presence of corrosion.

Electromagnetic Methods

The most commonly used NDE method (not considering visual inspection, hammer sounding, or manual excitation of the tendon) for post-tensioned structures is ground penetrating radar (GPR), which uses high-velocity electromagnetic waves to sense material changes in solid surfaces. It can be used to locate rebar in a deck or used on the interior of a box girder to find a tendon profile. Most often, this technique is used to locate internal tendon profiles, such as in the Wonderwood Connector Bridge (see case examples in Chapter 3). GPR can also be used to identify defects in tendons. Grout voids can be detected using GPR (Giannopoulos 2005), but the resolution of the data depends on additional factors, such as the presence of mild reinforcement and the depth of the duct. High frequency GPR antennae can gather images up to a depth of approximately 24 inches.

GPR is often used in conjunction with other NDE methods to corroborate findings. Hurlebaus et al. 2017 list the two most commonly used complementary techniques as ultrasonic echo and impact echo, which are both mechanical wave methodologies (Hurlebaus et al. 2017). GPR has also been used in conjunction with radiological techniques.

Another common electromagnetic NDE technology is infrared thermography (IRT). This technology uses the changes in materials' thermal properties to develop a subsurface image. In general, IRT can detect grout deficiencies and voids within ducts, but it cannot assess strand condition. IRT is a relatively easy technique compared to others, requiring only an area to set up an infrared camera and application of a thermal gradient.

Mechanical Wave or Vibration Methods

Mechanical wave and vibration methods rely on a physical process of sending either an acoustic or seismic wave through a material and measuring the reflection of those signals off of voids in the materials. These techniques are useful in identifying grout defects but they are not useful in identifying strand condition. As such, they will likely not provide meaningful information when employed on unbonded tendon. In fact, in an investigation of an existing unbonded post-tensioned parking structure, Puri and Moser (2007) decided against mechanical wave methods in favor of magnetic and radiological methods to supplement GPR data.

Ultrasonic echo sends a mechanically induced pulse through a material and measures the reflection/response of the material, which is helpful in identifying potential grout deficiencies. However, this technique does not identify problems with prestressing strands. It can be used on either metallic or nonmetallic ducts, and it is useful for depths of 2 to 12 inches.

Impact echo (IE) is a technique in which a metal ball is dropped on the concrete surface. Seismic waves pass through the material as far as they can go before hitting an "edge" and traveling back to a sensor. The time taken for the wave to travel back to the sensor is measured. The technique has been extensively used on concrete decks to detect delamination, but it can also be used in post-tensioning to detect voids and evaluate grout in tendon ducts. IE can work for both metallic and nonmetallic ducts as long as there are not any shrinkage cracks or voids between the concrete and the duct. Improvements have been made to the technique, such as the stack imaging of spectral amplitudes based on impact echo (SIBIE) technique (Muldoon et al. 2007). SIBIE stacks multiple IE measurements to develop a more robust method of observing material surrounding an air void.

In the early 2000s, an idea was proposed that used an ultrasonic method called C-Scan to detect various corrosion states in post-tensioning steel (Iyer, Schokker, and Sinha 2002). The

tool presented accurately detected corrosion in the strand, but the testing apparatus that was used did not lend itself well to in-field examinations.

Radiological Methods

Using X-rays to assess the condition of internal tendons is not common because of safety concerns and equipment expense, but it has been demonstrated to effectively identify damaged strands. Puri and Moser used radiological methods to accurately depict severed strands in existing post-tensioned structures (Puri and Moser 2007). The radiological method backed up data from other electromagnetic and mechanical wave methods. However, the time, effort, and expense required to conduct testing limit its potential to be used on a large scale.

Magnetic Methods

Mechanical wave methods tend to provide useful data only about grout deficiencies; magnetic methods tend to only provide useful data about strand condition. These techniques provide detailed estimates of the amount of lost steel in cross-section from corrosion and breakage. Magnetic flux leakage (MFL) is one such technique presented by Ghorbanpoor et al. (2000) that induces a magnetic field near prestressing steel to detect changes in cross-section from corrosion or breakage. Other reinforcing steel near the tendon can cause signal interference and affect results. This system works for tendons that are within 6 inches of the sensors, and as such works best with external tendons. In 2010, this technique was field investigated in service conditions to assess the Varina-Enon Bridge.

MFL is consistently capable of detecting loss of metallic area greater than 5% for many different types of tendon damage (such as corrosion, breakage, etc.), and it can be used in single or multistrand tendons (Karthik et al. 2019; Hurlebaus et al. 2017). Puri and Moser (2007) used magnetic scanning to accurately detect severed strands in an existing parking structure with unbonded monostrand that were not detected by GPR. This method may prove useful in detecting issues in unbonded tendons in bridge structures (Puri and Moser 2007).

Low-Destructive Evaluation Methods

LDE methods require invasive sampling to expose the post-tensioning tendon and these methods are the only testing alternative that provides accurate data on the degree of degradation of prestressing steel. LDE methods are common practice when severe deficiencies are evident on visual inspection of the outside surface of a structure (such as rust staining, leaking grease, etc.). One common method of low-destructive evaluation is drilling tendon high points to look for voids in the grout material, using a borescope to visually inspect and identify corrosion. To inspect internal tendons, the concrete cover is carefully removed to expose the post-tensioning tendon. Observations can be taken about the degree of corrosion and the presence of broken strands.

The "screwdriver test" is a simple test in which a thin, flat implement is wedged between wires in a strand to detect if any are broken. If any of the wires move, it indicates a severed wire. Gupta (2003) presents the pull-off method for calculating the remaining prestress in monostrand tendons after being exposed through statics. Roughly 2 feet of monostrand is exposed, and a hydraulic jack is used to pull on the strand at a specified force. The deflection of the strand from its horizontal profile is then measured and used to calculate the remaining prestress in the element. Both the screwdriver test and the pull-up method have been successfully demonstrated in the investigation of an unbonded post-tensioned parking deck (Gupta 2003).

Nondestructive Evaluation for Flexible Filler

The effectiveness of many NDE methods for PT inspection is influenced by the concrete cover, duct material, and rebar congestion, all parameters that are affected by the use of flexible filler. For example, the smooth HDPE pipe used with flexible filler is thicker than the typical corrugated duct used for grouting. In the particular case of the Wekiva Bridge, the bottom slab thickness and haunch were sized (thicker) to accommodate the internal bottom slab continuity tendons with flexible filler. Using smooth HDPE duct alone—without corrugations—may hinder the bond/create an air pocket between the encompassing concrete and the tendon, making some NDE methods inaccurate or inappropriate.

Repair

Problems with post-tensioning systems can necessitate various repairs. Repairs may be required of the PT tendon specifically (including the duct, filler material, or the strand); the anchorage and associated hardware; or the pour-back details that serve as part of the corrosion protection system, including pour backs at anchorages and at grout vents and ports. In addition, issues with a structure's PT system may require repair of the deviator blocks, diaphragms, or other points of contact between the PT tendon and the concrete section. Force loss in a PT structure may necessitate repair to the structure because of secondary effects, including structure cracking and joint issues.

Repairs, modifications, and issues with other parts of the structure, however, may have unintended effects detrimental to the PT system. Issues with deck integrity and water-tightness can lead to water penetration of the PT system. Modification of the deck in routine, planned deck-replacement operations has caused damage to the PT system because of inadequate concrete cover, the over-milling of the concrete surface, or both (see the case example of the Veterans' Glass Skyway).

Post-tensioning tendons rely on multiple layers of defense to protect the prestressing strand against moisture and corrosion mechanisms. A tendon repair may address deficiencies in the tendon duct material (sheathing), the filler material, or the prestressing strand.

Sheathing/Duct

Early U.S. PT bridge structures used metal duct; since the early 2000s, most PT tendons have been constructed with plastic duct. Issues encountered with a post-tensioning tendon's duct are influenced by the chosen duct material. Typically, internal tendons are detailed with corrugated polypropylene; external tendons are now commonly made with HDPE. Each material has its own characteristic resistance to damage.

Duct issues requiring repair include duct corrosion, duct misalignment, duct kinking at deviation points, duct splicing failures, duct bursting during filler injection, and duct damage of unknown origin. Most duct issues occur during construction. Issues encountered during construction, if caught prior to filler injection, are repaired to pass tendon pressure tests, which are often set as a project requirement before the injection may proceed. Duct bursting has been documented in multiple structures during filler injection. In some cases (such as the issues described in the case example of the Veterans' Glass Skyway deck replacement), duct damage can occur during later structure modification. Duct damage also occurs during invasive tendon investigation and must be repaired to ensure adequate tendon protection.

Currently, repair recommendations to address duct issues encountered in bridge construction are not available from the Post-Tensioning Institute. However, its repair committee, DC-80, has published recommendations and guidance documents for the repair of sheathing of the more uniform scenarios encountered with the single-strand tendons used in building construction.

Filler

Issues with cementitious filler materials, including nonproprietary and proprietary grouts, have been well documented since the early 2000s. Grout deficiencies in external tendons have been documented in several structures (for example, the Sunshine Skyway in Florida and the Wando River Bridge in South Carolina). Problems with filler materials have included the presence of excessive bleed water, the formation of soft grout (Wonderwood Connector, see Chapter 3), and the presence of contaminants (Veterans' Glass Skyway, see Chapter 3). Causes of poor-quality grouts have been identified through many owner-instigated investigations and research efforts, and have included inaccurate bag weights affecting the mix proportions in proprietary grouts, improper mixing technique, mixing of different grout materials in the same tendon, insufficient clear passage in the duct potentially causing grout separation (Wonderwood Connector, see Chapter 3), and improper injection procedures (including issues with venting, pressure, injection speed, and other methodological causes).

Deficiencies in grout in internal tendons pose significant problems when they occur. As internal tendons are contained entirely within a portion of the concrete cross-section, access is limited for the purposes of both inspection and repair. The difficulty of identifying problems in internal tendons has necessitated research efforts to identify effective methods. When problems with the grout in internal tendons have been identified, the removal and replacement of the tendon is not feasible. The current in-progress repair of the Wonderwood Connector in Florida (see case examples) is a prime example of the unique challenges and actions required to remediate internal tendons with deficient grout.

The severity of the repair required when filler material is deficient has instigated a number of responses. Several research efforts have been undertaken to identify and address deficient grout (Alvarez and Hamilton 2002; Hamilton et al. 2014; Randell, Aguirre, and Hamilton 2015; Torres et al. 2018). Problems with grouts have compelled some agencies to consider other options for filler material and prestressing strand material to ensure soundness and robust corrosion protection of the tendon. Further, issues identified in a few in-service PT bridges have compelled significant response by industry groups and grout manufacturers to improve grout quality and injection procedures.

Strand

Damage to the prestressing strand, when encountered, is often a side effect of the compromise of some other protection layer of the PT tendon. Types of strand damage include electrochemical corrosion (rusting) of the strand, mechanically caused damage (nicking or severing of wires or the strand), and hydrogen embrittlement. Strand damage may be identified through rust staining of adjacent grout or nearby concrete surfaces. In extreme cases, relaxation of the tendon may be evident, indicative of force loss; in some cases, force loss may occur without obvious visual cues. Because some grouted tendons can permit force redevelopment (depending on their contact with the main concrete cross-section), strand damage can remain unidentified until it reaches a critical threshold.

Advances in Post-Tensioned Bridge Design in the United States

Since the introduction of post-tensioned bridge structures to the United States, several advances have improved the durability of these systems. Key changes include the following:

- Improved quality control of grout, including mixing and injection procedures
- Improved grout materials, including thixotropic prebagged grouts
- Improved detailing, particularly at connections
- Introduction of grout certification programs
- Introduction of flexible filler materials
- Enhanced inspection methods (by some states)
- Provisions and detailing for tendon replacement (by some states)

The use of alternative filler materials, such as microcrystalline waxes, has constructability, design, and maintenance implications, but this use can provide corrosion protection to tendons while permitting later tendon removal.

International Experience

The introduction and evolution of post-tensioning in bridge structures have always been tied to international practices and technology transfers, including both the early contributions of Magnel and Freyssinet (both French engineers) and the early examples of post-tensioning issues and repairs.

In 1985, the collapse of the Ynys-y-Gwas Bridge, attributed to elevated chloride levels at segment joints, instigated a serious reconsideration in the United Kingdom of the durability of post-tensioned bridges, despite good service performance of these structures and few documented cases of severe corrosion (Raiss 1993; Woodward 1989). By 1991, the Department of Transport's preferences in design practice had shifted from the use of internal tendons to external tendons (Robbins 1991). In 1992, the U.K. Concrete Society and the Concrete Bridge Development Group established a working group to investigate and address concerns related to concrete bridge durability. Simultaneously, a temporary ban was placed on "new bridges of the grout-duct post-tensioned type" (Department of Transport 1992). The group worked to develop interim and revised guidance on PT design, detailing, specification, and construction methods, and on testing methods to evaluate PT structures (Raiss 1993).

A 2009 inspection of the Sawasokogawa Bridge, a post-tensioned concrete composite girder bridge in Japan, revealed corrosion and concrete spalling of the deck near the intermediate piers. An extensive repair was performed to remove the deck slab "cables," to replace the deck with a reinforced concrete deck, and to add strengthening reinforcement by additional external tendons. Causes of the initial corrosion were attributed to water and contaminant intrusion into the structure near the fulcrum, exacerbated by the heavy use of deicing salts. Salinity testing of the concrete found chlorides well exceeding the recommended limits (2.7 kg/m^3 versus 1.2 kg/m^3) (Nagatani and Tajiri 2019).

The Petrulla Bridge was a viaduct built in Italy in the early 1980s that was devoted to vehicular traffic, mostly vehicles transporting raw agricultural materials, including fertilizer. The structure collapsed in 2014. The failure was attributed to several factors: corrosion instigated by delay between stressing and grouting, exposure to fertilizer, a lack of gap between the ducts, and inappropriate grout for tendons. Investigations found that grouting occurred after a sufficient time lapse that allowed water to accumulate in some locations, leading to aggressive corrosion. Testing of the grout revealed a high chloride content in the tendons: 0.24% by weight of cement versus the limit (per AASHTO-LRFD, PTI M55) of 0.08% (Anania, Badalà, and D'Agata 2018; Virmani and Ghasemi 2012).

CHAPTER 2

Survey

An online-based survey was distributed to the 50 state departments of transportation in February 2020. Initial survey distribution occurred that month, with subsequent attempts to contact agencies to gather as many responses as possible. The survey (included in the appendix) gathered information on the state transportation agency's experience with post-tensioned bridge system design, construction, maintenance, inspection, and repair. All 50 of the DOTs responded to the survey (see Figure 7). Five responses were partial or incomplete. One state (Illinois) opted not to participate, citing lack of relevant experience; however, this notification was counted as a survey response. This chapter covers findings and trends from the survey and subsequent communications with state DOT personnel.

Experience

Forty-four state agencies report having post-tensioned structures in their inventory (see Figure 8). Six respondents do not have post-tensioned structures (Arkansas, Iowa, Maryland, South Dakota, Tennessee, and Wyoming). The states without post-tensioned bridge structures provided several reasons for not building PT structures, including lack of familiarity, concerns regarding quality and durability, lack of need, and lack of a local, established industry presence. Of the state DOTs without PT structures, several communicated no anticipated future need for such a structure. Twenty-three states report having conducted repairs on their PT structures (see Figure 9); more than half of the state DOTs with PT structures have performed some type of repair.

The structure types included in state DOT inventories varied widely (see Figure 10). No attempt was made to quantify the number of structures of each type in state inventories. Segmental bridge structures are found in a majority of the states with PT structures in their inventory, with 24 states having cast-in-place segmental structures and 30 states having precast segmental structures. Half of all states have PT decks (25), PT pier caps (27), and PT spliced girders (25). States described "other" types of PT structures in their inventory as

- Hybrid pretensioned, post-tensioned girders (Alaska)
- Precast channel units (Alabama built some in the 1970s; New York built with a patented channel shape starting in the 1990s)
- Columns, U-beams, straddle beams, C-piers, footings (Florida)
- Precast panel slab bridges with transverse PT bars (a significant quantity built in the 1970s and 1980s and discontinued because of poor performance, Louisiana)
- Hold-downs at end piers (Ohio)
- Arch ribs (Oregon)
- Retaining wall tie-backs for soldier pile walls, sheet pile walls (Wisconsin)

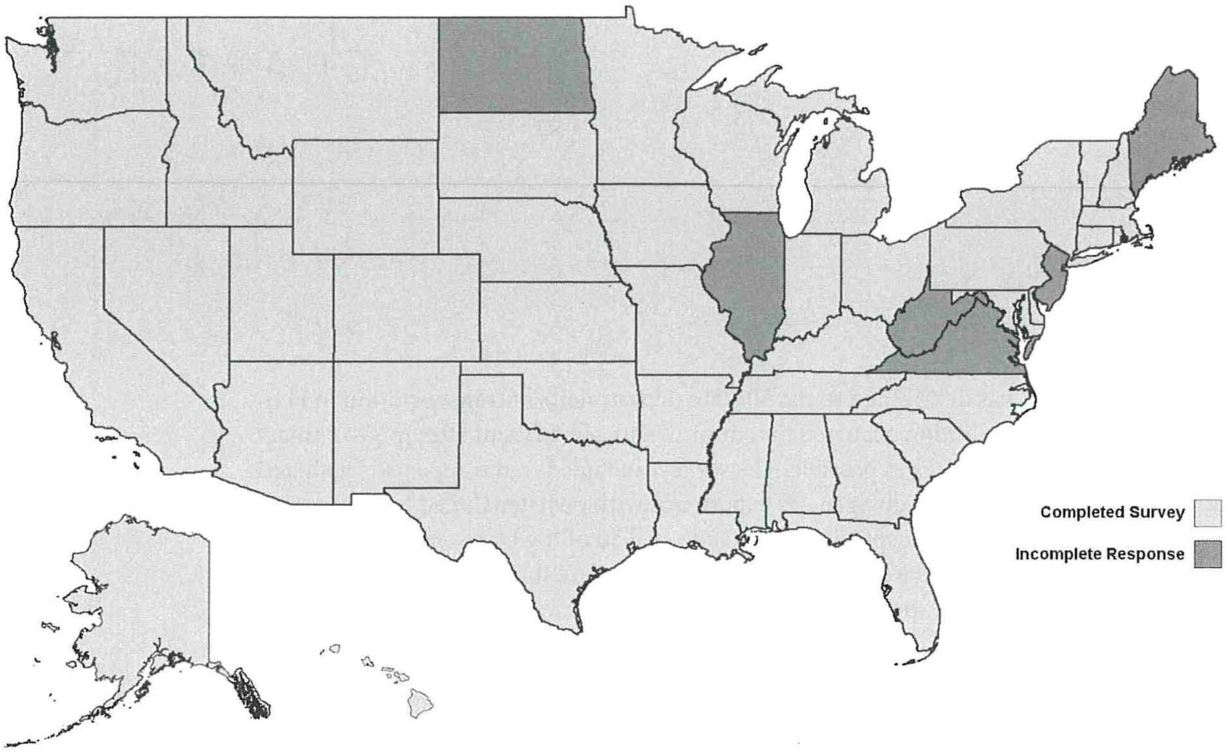


Figure 7. ***Survey participation by state DOTs.***

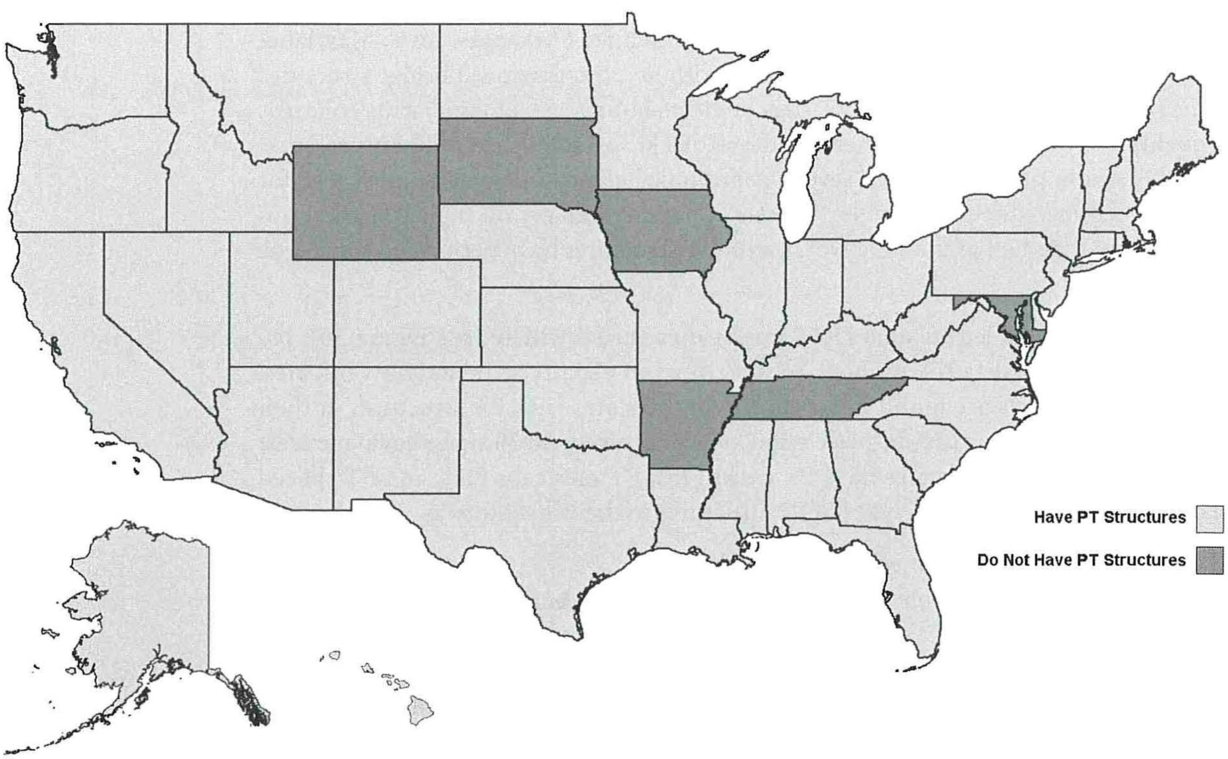


Figure 8. ***States with post-tensioned bridge structures.***

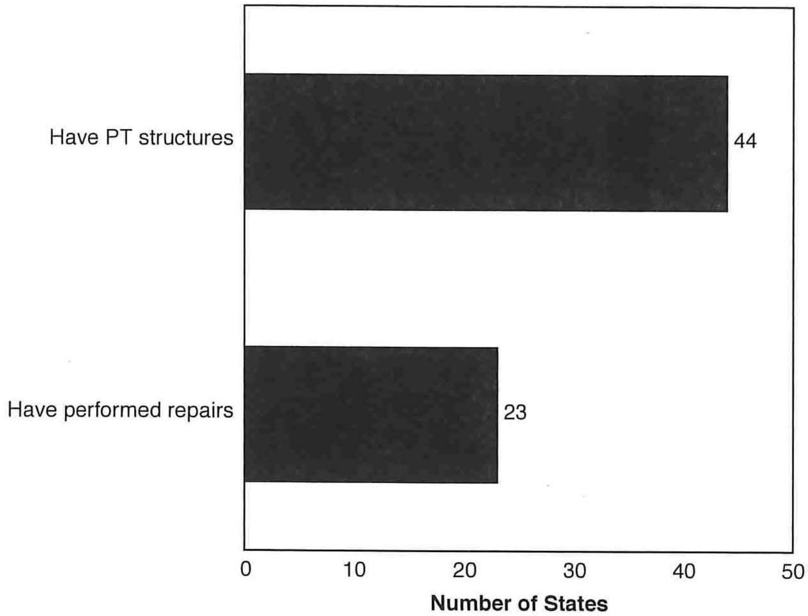


Figure 9. States with post-tensioned bridge structures and with repair experience.

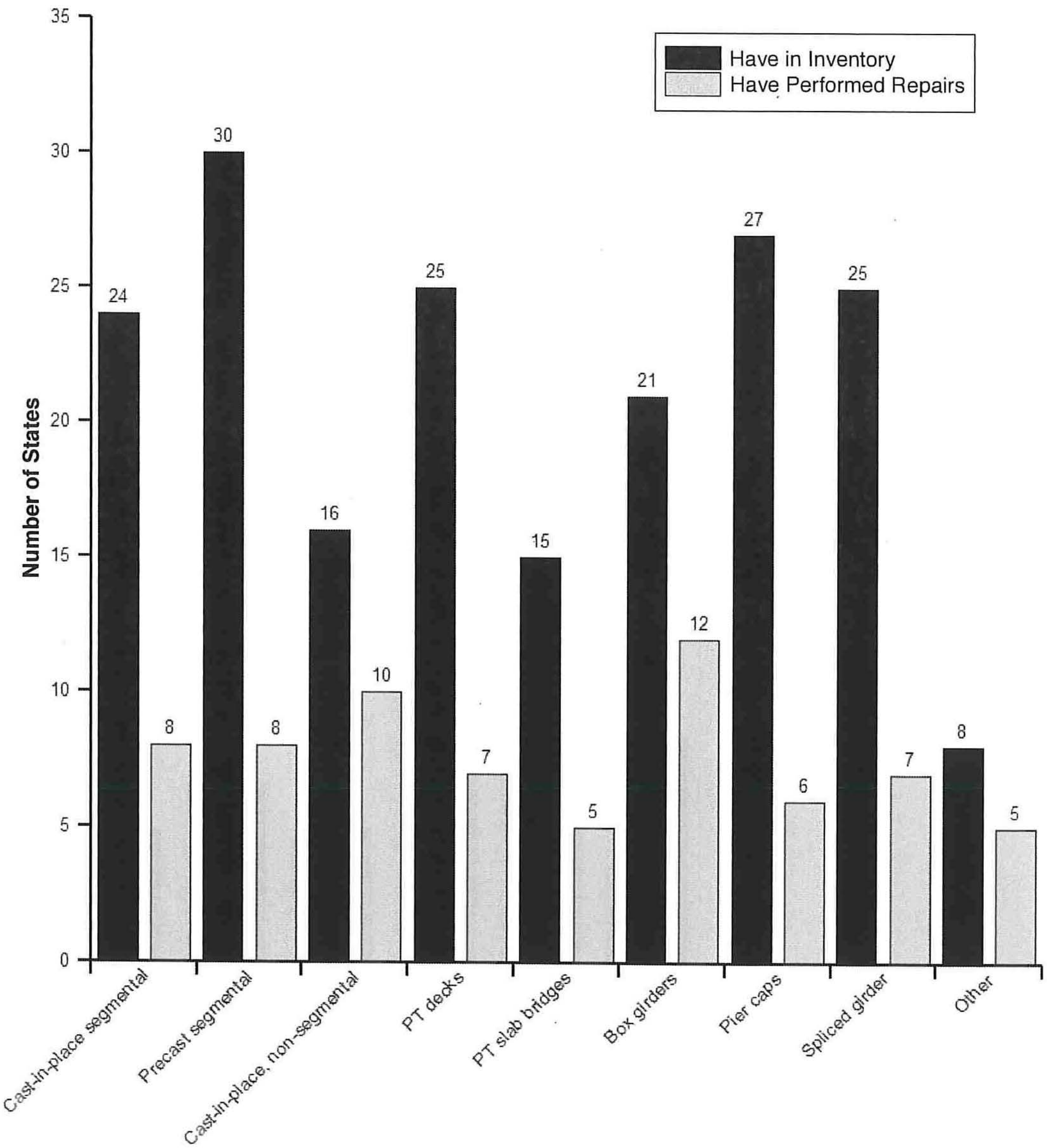


Figure 10. Post-tensioned structures, by type.

States have performed repairs on every type of PT structure (see Figure 10). Adjacent precast box-girder structures were not covered by the survey; the reader is referred to *NCHRP Synthesis 393* for information on this topic (Russell 2009).

Design and Construction

A series of questions in the survey were aimed at identifying efforts by state agencies to ensure current, up-to-date practices during construction and design. These included questions related to agencies' PT-specific specifications (if any), the inclusion of protection levels in design approach, and quality control/assurance practices during construction. In general, a uniformity in approach is not apparent, with a variety of guidance documents referred to, certification programs specified, and quality control/assurance and design approaches used. This is not surprising, given the wide range of PT experience from state to state (see Figure 11), with some states having nearly 3,000 PT structures (California) and others having five or fewer (Delaware, New York, Rhode Island, South Carolina).

Agencies were asked to specify reference documents used in developing their specifications. In general, state specifications are informed from guidance documents such as the PTI/ASBI M50 Guide Specification for Grouted Post-Tensioning, the PTI M55 Specification for Grouting of Post-Tensioned Structures, and the AASHTO-LRFD Bridge Construction Specification.

A notable number of state DOT agencies are modeling their post-tensioning practices on specifications and actions from key states, most often Florida (referred to by seven states: Alaska, Louisiana, Minnesota, New Hampshire, Ohio, Oklahoma, and South Carolina) and California

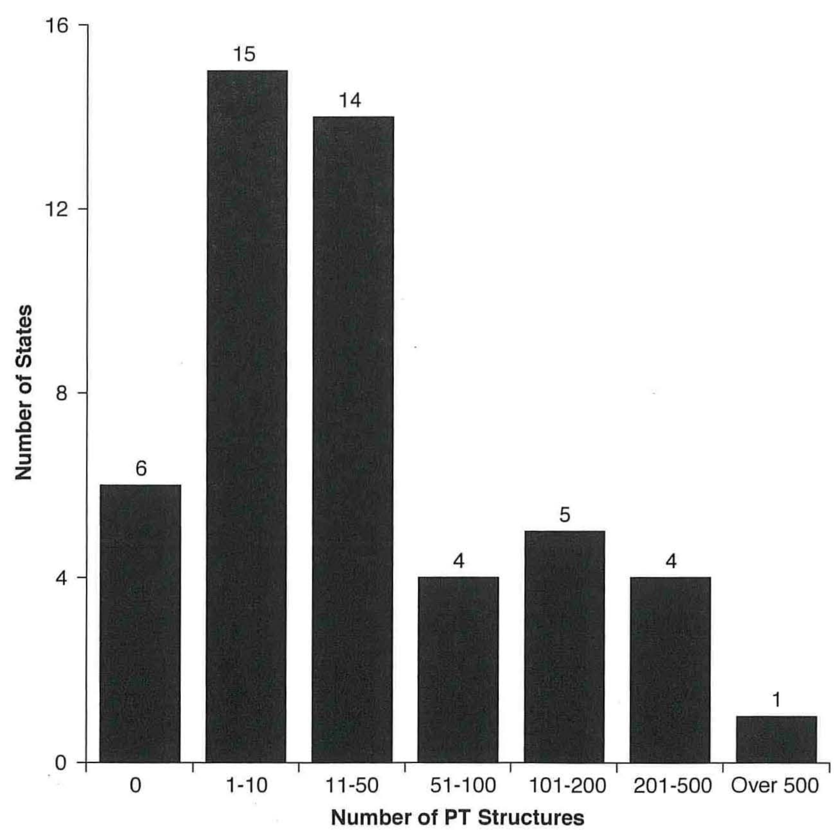


Figure 11. Quantity of PT structures in inventory.

(referred to by four states: Alaska, Arizona, Hawaii, and Nevada), in the development of their PT specifications. Other states were referring to a neighboring state; states referred to in this vein include Massachusetts (referred to by New Hampshire and Rhode Island), Washington (referred to by Idaho), and Vermont (referred to by New York). A few state agencies are relying on project-specific specifications for their post-tensioned work (Louisiana, for example).

Most state DOTs have updated their PT specifications in the last 2 to 7 years. Given this effort, and the fact that many states (14) are referring to PTI/ASBI M50 Guide Specification for Grouted Post-Tensioning and PTI M55 Specification for Grouting of Post-Tensioned Structures in their specification updating, it appears that the lessons learned since the grout problems uncovered in the early 2000s are making their way into DOT guidance documents, though not universally. Additional efforts to ensure nationwide awareness of improved practices for PT construction may be warranted.

The survey asked state DOTs to identify if a specific protection-level design approach was required for their PT structures. The International Federation for Structural Concrete (fib) and the PTI M50 document suggest a tiered approach to strategize the design of the corrosion protection system for a post-tensioned structure (see Figure 4 and Table 1). A structure is designed with a designated protection level (PL), which guides the design of protective elements. The PL is selected on the basis of the exposure of the structure and the aggressiveness of the structure's environment (see Figure 4). The concept of designing for a particular protection level is accomplished either through explicitly naming a PL-requirement (done by some states) or by requiring the same protective elements. In interpreting the survey responses, it is important to note that the concept of designing for a particular protection level may be new to a state's specifications; no effort was made to identify when states included "PL" considerations in their specifications.

Most states (23) with PT structures in their bridge inventory do not indicate a design requirement for a particular protection level of their post-tensioned structures (see Figure 12). Only some states are specifying—either directly or through equivalent requirements—a particular protection level. Michigan is requiring the most stringent protection methods for its

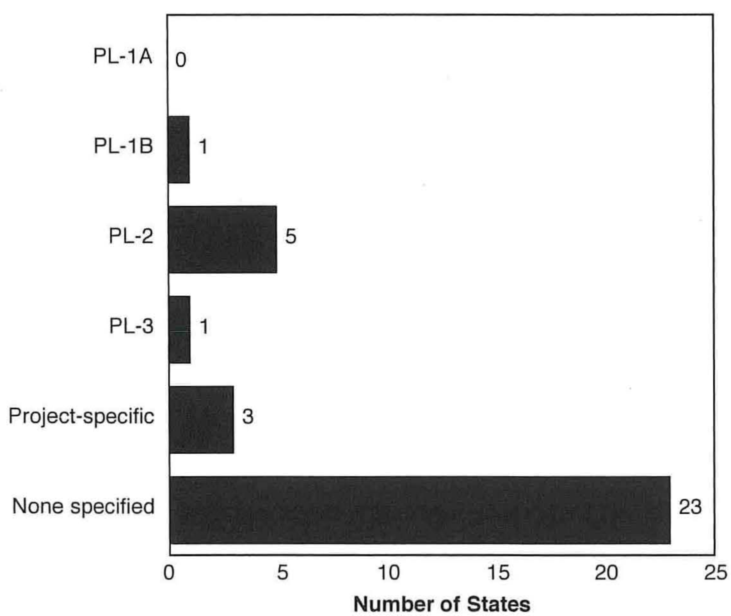


Figure 12. Protection levels for PT structures.

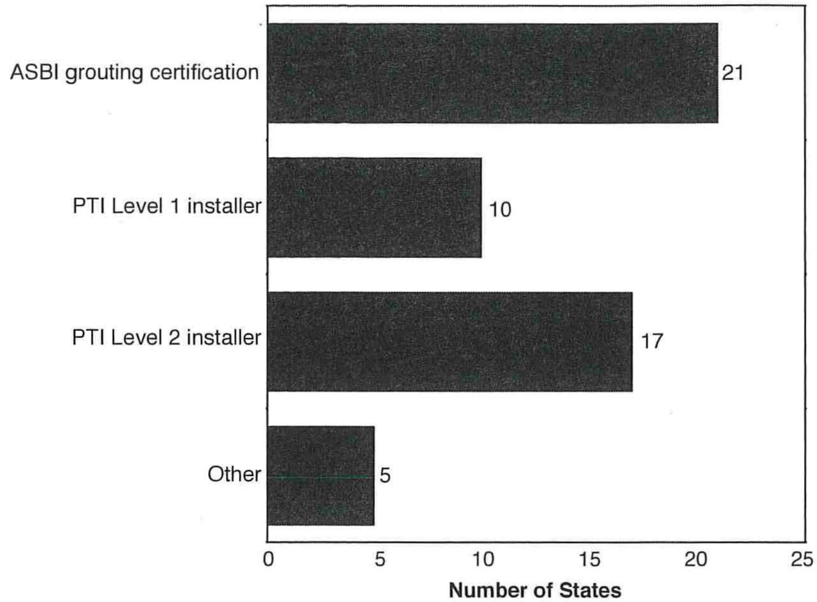


Figure 13. State requirements for PT installer qualifications/ certifications.

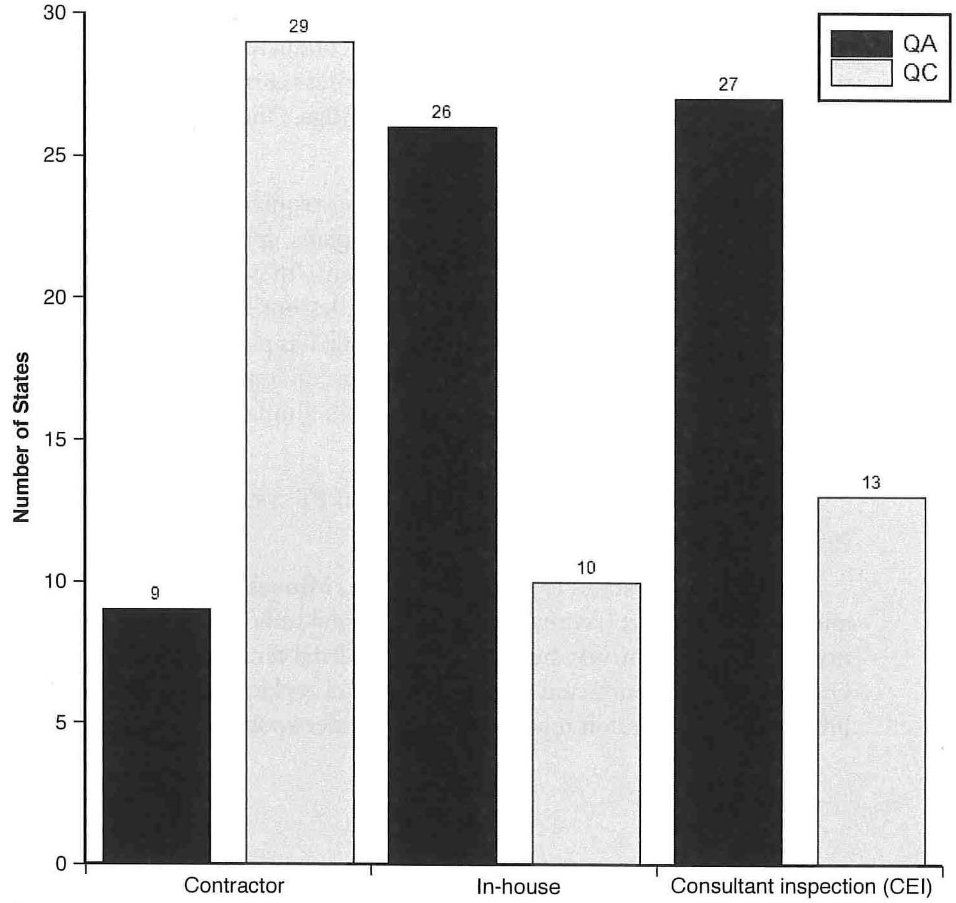
PT structures, PL-3. Five states (Louisiana, Minnesota, Mississippi, New York, and Rhode Island) are specifying PL-2, although Minnesota notes that it has been unsuccessful in implementing appropriate duct couplers to satisfy PL-2 in its precast segmental projects. Colorado is implicitly using PL-1B by requiring the same components. Nebraska, Pennsylvania, and Wisconsin are specifying protection levels on a project-by-project basis, using the particular structure's exposure as a consideration in the assigned protection level.

To identify how many states are formalizing the qualifications of PT installers, agencies were asked to identify their requirements for PT installer qualifications/certifications (see Figure 13). It is important to note that states may specify more than one certification in their requirements, and that certifications are role dependent. Twenty-one states require the ASBI grouting certification. Seventeen states require installers to have the PTI Level 2 installer certification, with another 10 requiring the PTI Level 1 certification. Five states have "other" requirements (for example, in Florida, the state's DOT-specific Construction Training and Qualification Program, CTQP) to become a qualified grouting technician. The FDOT CTQP qualifications for grout/PT installation can be partially satisfied with the ASBI grouting certification and PTI certification, respectively.

States were asked to indicate what types of personnel perform both quality assurance and quality control on their post-tensioned structures, selecting all that applied (see Figure 14). Most states are relying on a combination of in-house staff and consultant engineering inspectors to perform quality assurance tasks.

Repairs

A majority of states (23) with PT structures in their inventories (44) have experience with PT repair (see Figure 15). Repairs (in general, not just PT repairs) are most often performed by contractors (31), especially in cases with extensive repair. Some states occasionally perform repairs with in-house staff (New Hampshire and Oregon), though these states also use contractors.



Note: QA = quality assurance; QC = quality control.

Figure 14. Personnel performing quality assurance and quality control.

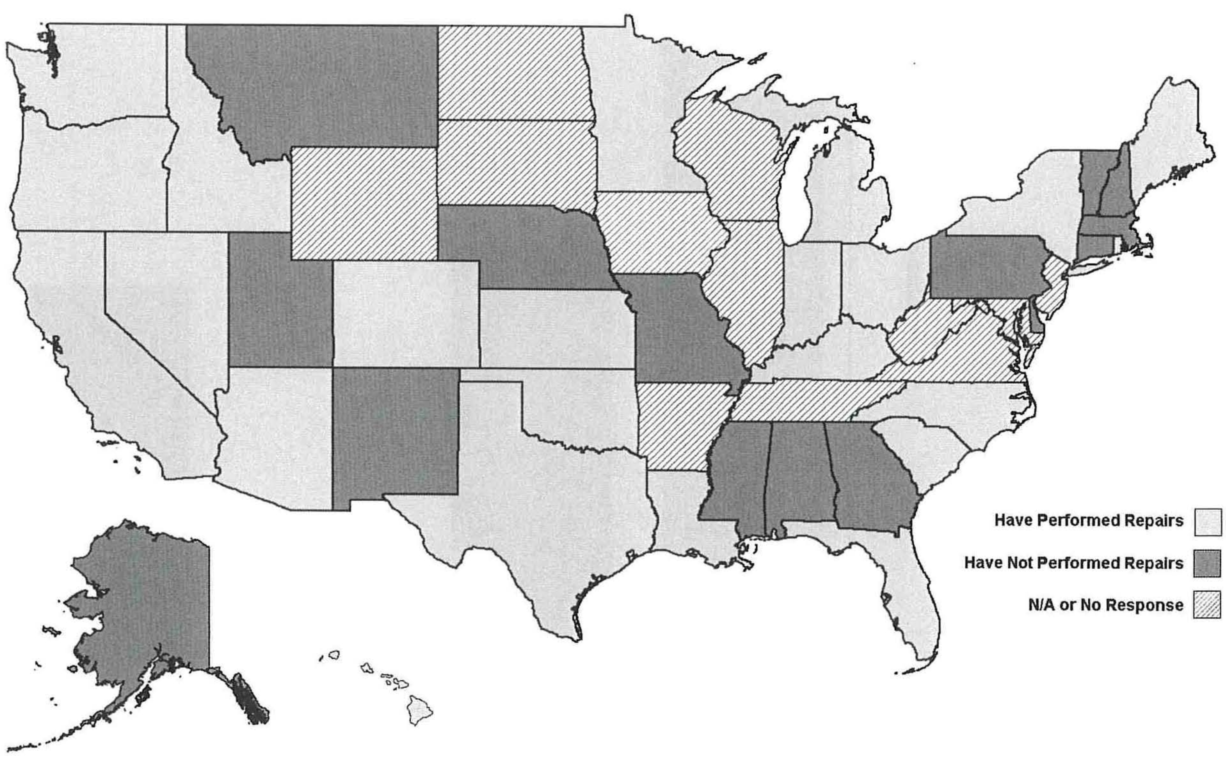


Figure 15. Experience with PT repair by state.

Additional questions were aimed at identifying trends among repair occurrences and potential causes (see Figure 16). Seventeen states have conducted repairs to PT systems during construction. Ten states have performed repairs to address corrosion issues. Nine states have performed repairs of or have replaced a deck on a PT bridge. One state (Hawaii) has performed repairs to a PT bridge following a vehicle impact.

Though it is understood that each situation requiring repair is unique, agencies were asked if they had any standard or commonly used plans, specifications, procedures, or details for PT repairs or, specifically, for tendon replacement. These questions were included to identify an agency's attempt to formalize repairs, transfer lessons learned from one case to another, or standardize its response. Only one state, Minnesota, has published standard procedures for remedial grouting. PTI has published recommendations on appropriate sheathing repair approaches for monostrand tendons in building construction. Similar guidance is not published for common repairs performed in the bridge industry.

States reported experience with a variety of PT system repairs, inspection, and maintenance actions (see Figure 17).

A notable seven states (Florida, Louisiana, Minnesota, New York, Oregon, South Carolina, and Virginia) report having performed external unbonded tendon replacements (Virginia did not complete the survey, but did report external tendon repair on the Varina-Enon Bridge). Only Minnesota conducted an internal tendon replacement. Florida has investigated the feasibility of internal tendon repair with the Wonderwood Connector, and it is moving ahead with

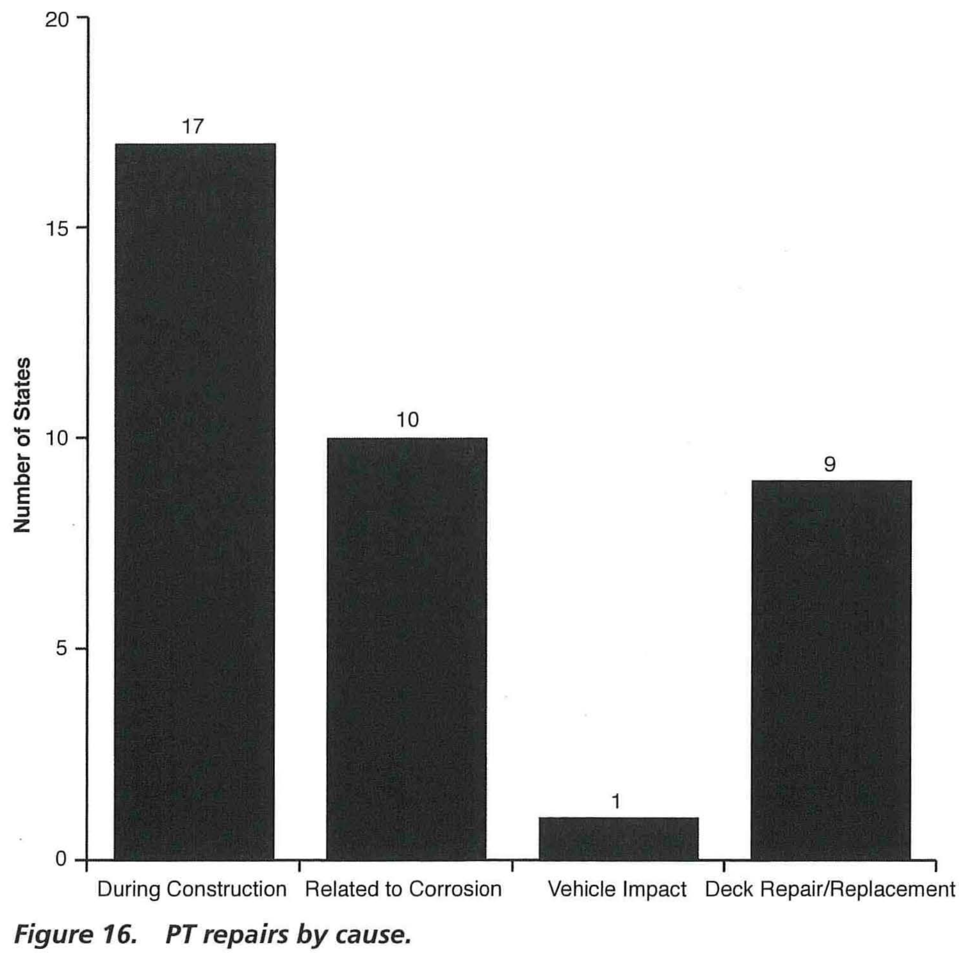
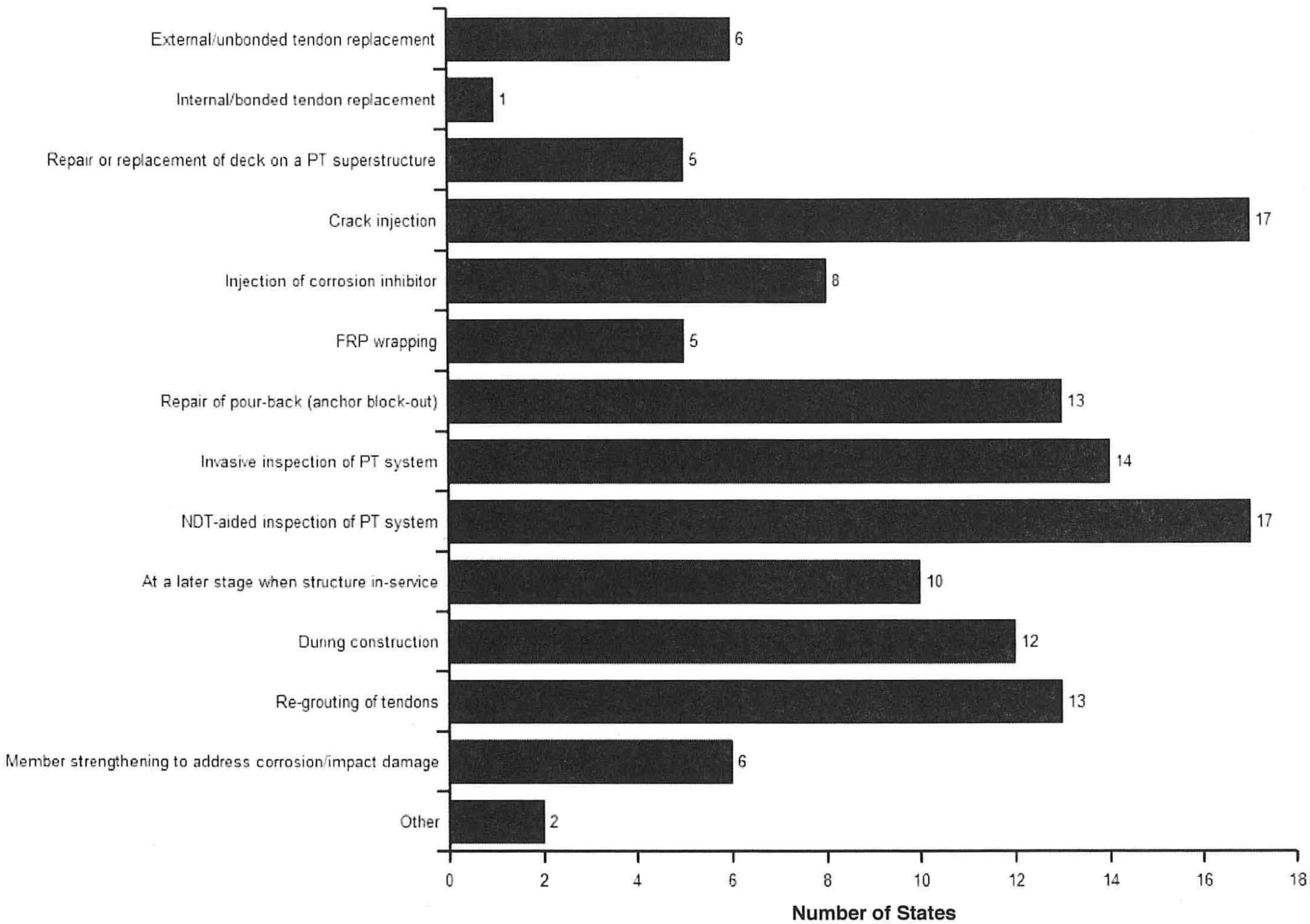


Figure 16. PT repairs by cause.



Note: NDT = nondestructive technique.

Figure 17. Types of maintenance, inspection, or repairs performed.

an alternate repair approach (involving drying of tendons and injection with corrosion inhibitors; see Wonderwood Connector case example, Chapter 3). Crack injections of PT structures have been performed by 17 states. The use of injected corrosion inhibitor is reported by eight states: California, Florida, Louisiana, North Carolina, Ohio, Oklahoma, South Carolina, and Texas. Most states report using proprietary corrosion inhibitors in these efforts. Fiber-reinforced polymer (FRP) wrapping of PT structures is reported by five states. Thirteen states have regrouted tendons, and six states have provided additional member strengthening to structures to address corrosion or impact damage.

To identify potential causes for later repair, agencies were asked to comment on particular aspects of post-tensioned construction. The survey asked respondents to evaluate the following:

1. Had the agency encountered problematic construction details? (Figure 18)
2. Had the agency encountered problematic construction techniques or methods? (Figure 19)
3. Had the agency encountered problematic materials, in the context of PT construction? (Figure 20)

Of the 35 responding states, nearly half (17) report issues with problematic construction details. States were asked to identify problematic construction details with which they had

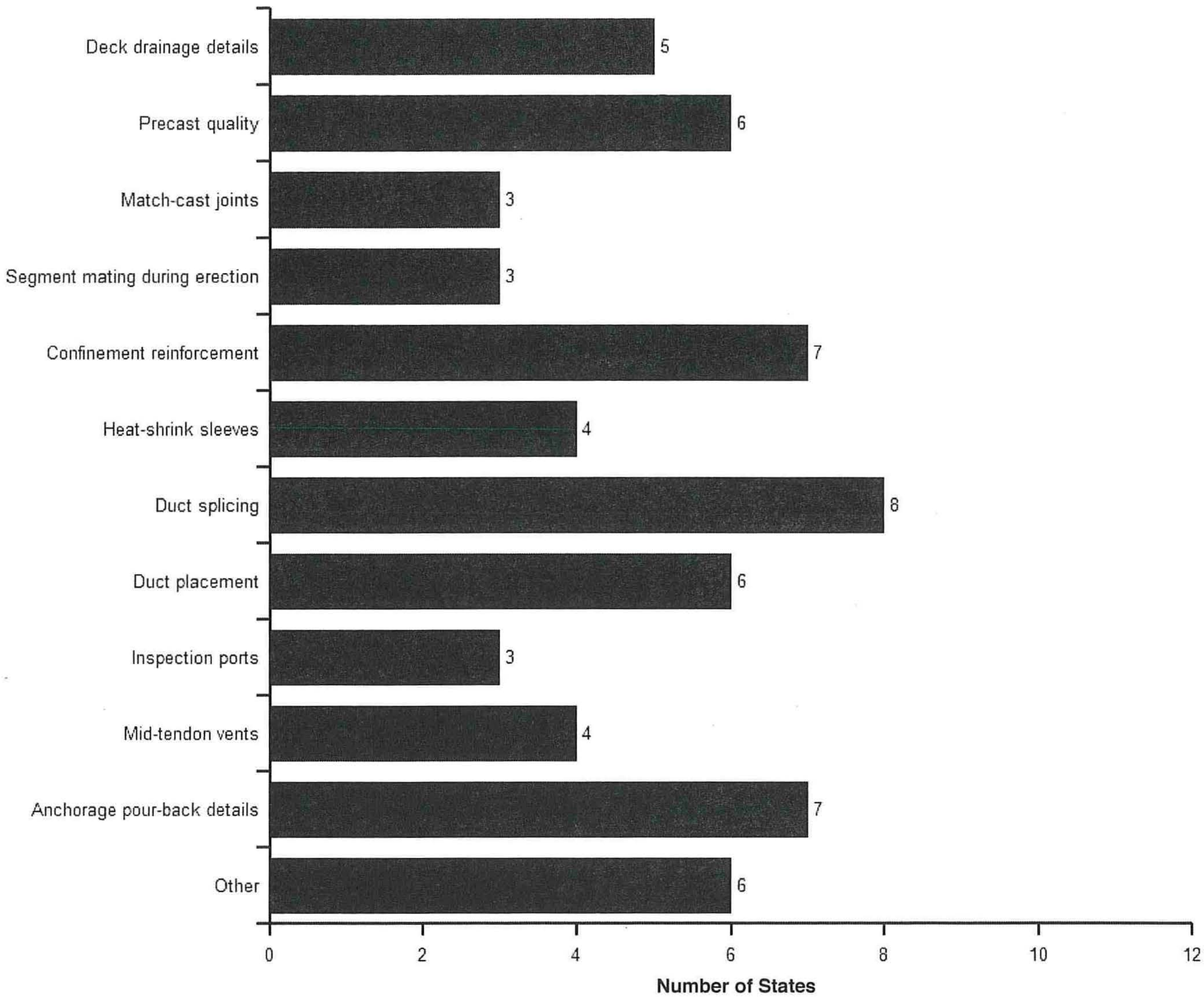


Figure 18. Problematic construction details.

encountered issues (see Figure 18). The most commonly reported problematic details included duct splicing details (eight respondents), anchorage pour-back details (seven respondents), and confinement reinforcement (seven respondents). Although not a specific detail, nor one unique to post-tensioned structures, congestion of rebar and other hardware (in this case, PT) was a frequent issue requiring careful consideration by the detailer, according to several of the surveyed states.

Six states identified other concerns they had encountered during construction of their PT structures, including problems with large shear keys cracking during erection and conflicts with blisters and/or deviators, deck-level grout tubes, and nonmetal ducts (Oregon). In communications with several agencies outside of the survey, several expressed issues past and current with deviator/blister geometries. Common issues ranged from incompatible alignments to excessively sharp corners at deviators, leading to kinking or damage to the tendon duct. The review of several case examples (see Chapter 3) reveals that duct conflicts at diaphragms and deviator locations were a recurrent problem for years before modifications to connections and refinement of the standard practices improved these details. Still, geometry issues remain. However, a detailing shift instituted in Florida in 2014 may provide a solution for other agencies: the

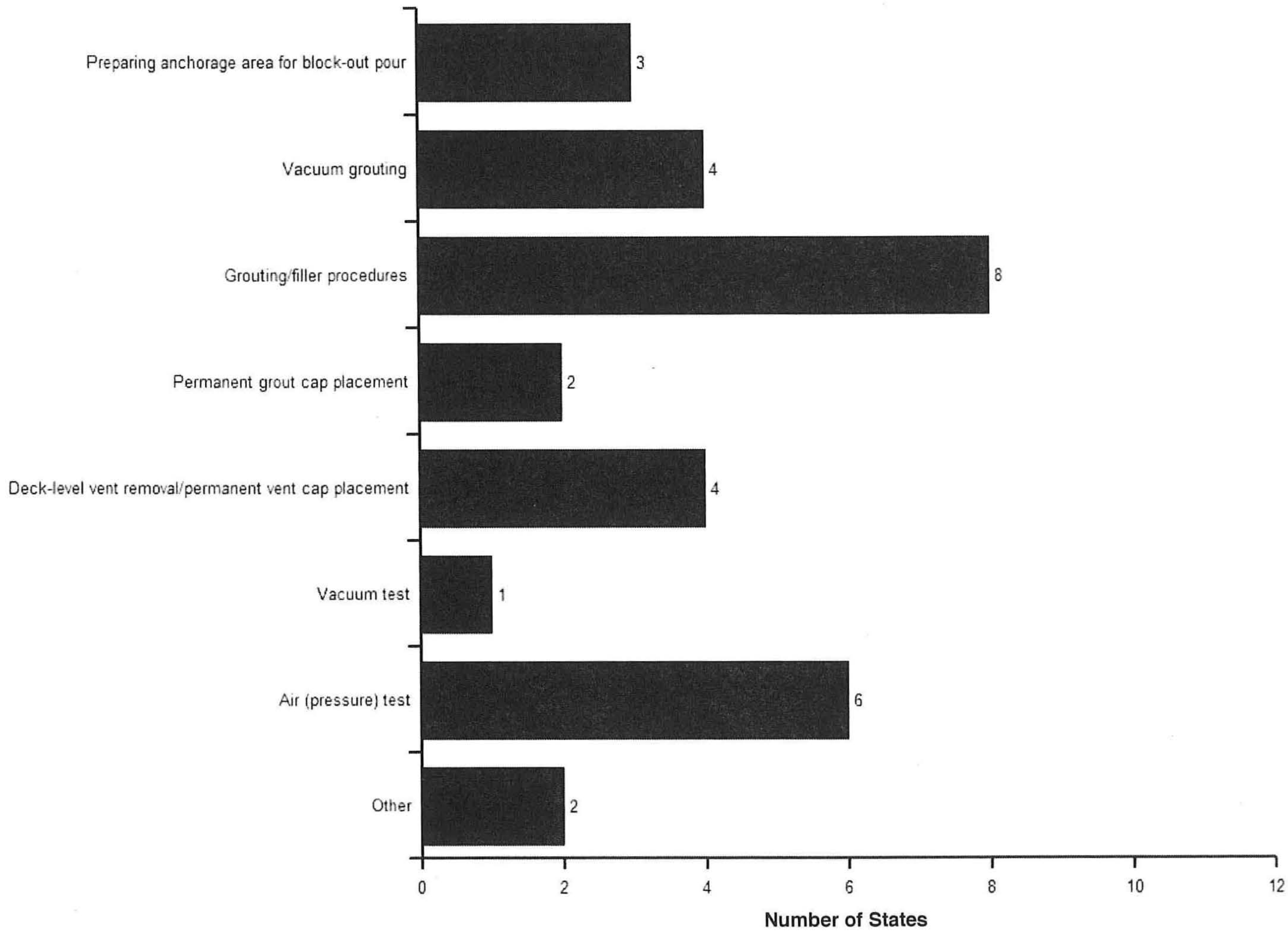


Figure 19. Problematic construction methods.

diabolo-shaped deviator type. The appeal of this detail is the gentle angle change at the entrance of the deviator void, which eases the transition of the duct profile at deviation locations.

Respondents less frequently identified construction techniques and methodology as problematic (12 respondents), suggesting that recent efforts to educate personnel through certification may be proving beneficial as a way to improve the state-of-the-art construction of post-tensioned bridge structures. Of the 36 respondents choosing to comment, 12 answered "yes" that a construction technique/methodology was a concern. Issues identified by those states (see Figure 19) included grout filling procedures, air pressure test procedures, and vacuum test procedures—all of which occur during the injection process.

No attempt was made in the survey to develop a timeline for the identified problematic methods/techniques. Some agencies are still encountering and repairing issues with structures built in the 1980s and 1990s, while others are still addressing tendons filled with the high-chloride-containing proprietary grout (which has since been removed from distribution). These agencies may have responded with such repairs in mind.

Still, states report issues with ensuring a completely full tendon without voids, and with passing pressure/vacuum tests. One state stressed that it was "important to have personnel requirements in special provisions for vacuum grouting personnel to make sure staff performing this work are qualified and well experienced in vacuum grouting."

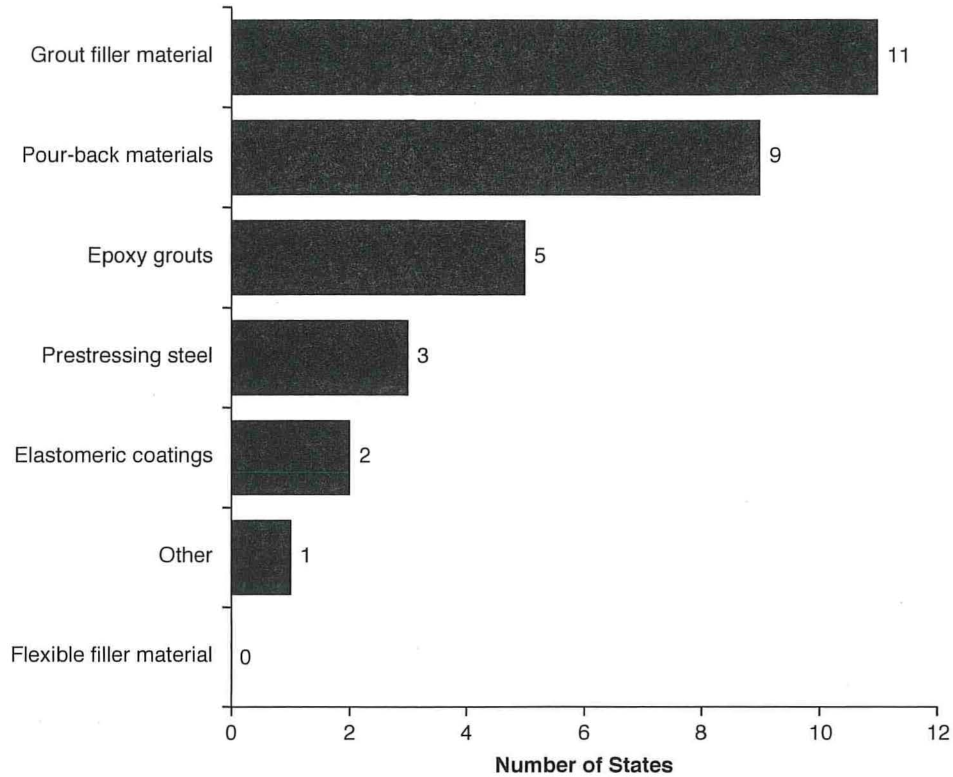


Figure 20. Problematic materials used in PT.

Four states identified having issues with the removal of deck-level vents and the placement of the permanent caps. In general, the details for these areas are nonspecific, with methodology left up to the contractor. Several states have reported issues with those details and with the methods used to seal off deck-level vents, elaborating that deck-level vents are often left sticking up unprotected at the deck level, where they can be easily damaged by personnel and moving equipment. Other expressed issues related to deck-level vents include difficulty removing the vents, difficulty placing the permanent cap, and issues with preparing the areas for the secondary pour backs.

Other reported construction "methods" include issues with cast-in-place joints and deck/panel alignment.

Fifteen of 36 respondents reported dissatisfaction with specific materials used in post-tensioning, with the primary material of concern being grout filler material (see Figure 20). Materials most often identified as problematic included grout filler materials (11 states) and pour-back materials (nine states). Another five states identified issues with epoxy grout materials. The Oregon Department of Transportation reported dissatisfaction with nonmetal ducts but did not provide further explanation. No states report issues with flexible filler, but this is not surprising given its relatively recent introduction to the U.S. bridge industry.

States reporting issues with grout filler material provided further comment suggesting that their response was informed by past issues, before the introduction of prebagged thixotropic grouts. Several states specifically called attention to previous problems with excessive bleed water and chloride contamination. States describing issues with pour-back materials further specified that these materials had low workability and issues with shrinkage cracking, in their experience.

Inspection and Maintenance

Many states report performing nonroutine inspections of their PT structures (see Figure 17), including invasive inspections (14) and nondestructive technique-aided inspections (17).

Nondestructive testing methods have been used in inspections, or investigated via research for potential use in inspection, by many states (see Figure 21). Most states (29) are relying on visual methods of inspection for their post-tensioned structures, although others have investigated other nondestructive test methods. Less commonly, electromagnetic wave propagation (i.e., infrared thermography, impulse radar, ground penetrating radar; 10 states) and mechanical wave/vibration methods (i.e., acoustic emission, impact echo, ultrasonic, hammer sounding; 11 states) have been reported as methods used for PT assessment. Four states (Florida, Oregon, Pennsylvania, and South Carolina) have used electrochemical methods (i.e., half-cell potential). Indiana, Massachusetts, and Pennsylvania report using or investigating radiation methods (i.e., X-ray diffraction, radiography). One state (North Carolina) has used direct measurement of tendon force.

A handful of state DOTs have formally investigated various methods of nondestructive testing techniques for evaluation of PT structures, including Pennsylvania (Naito, Jones, and Hodgson 2010; Naito and Warncke 2008), Florida (Azizinamini and Gull 2012), and Kansas. Each of these states' departments of transportation have collaborated with local universities in formal efforts to research available nondestructive test methods.

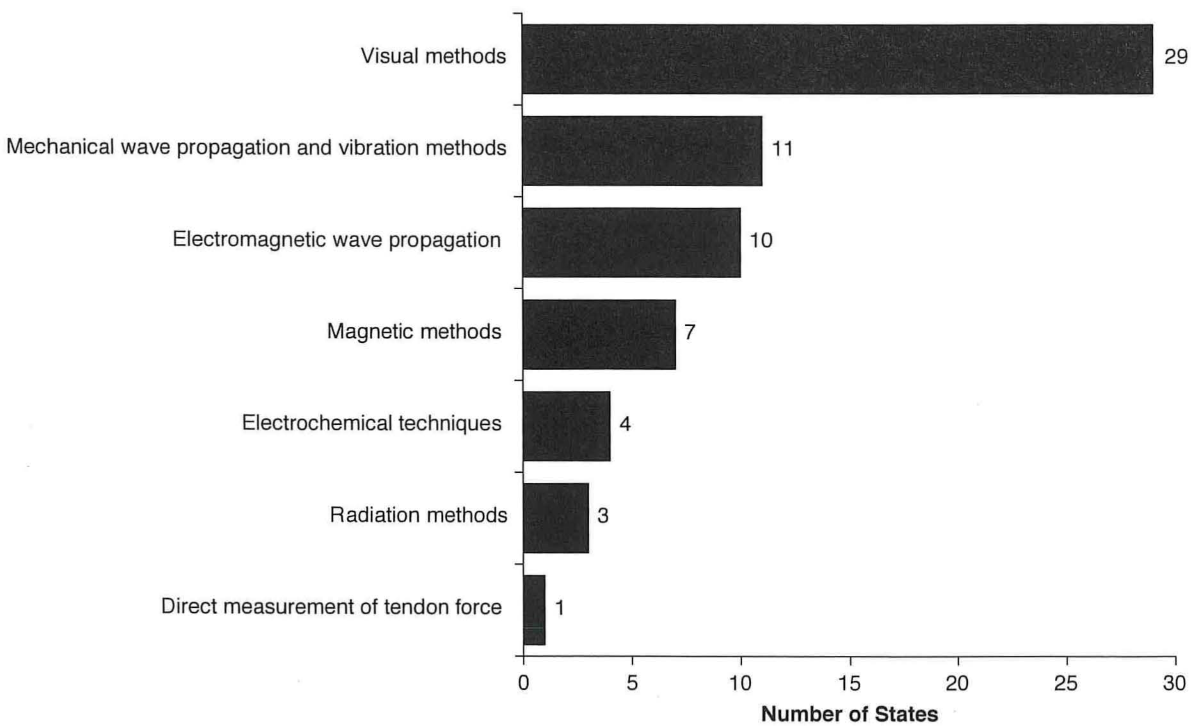


Figure 21. NDE methods for PT inspection.

CHAPTER 3

Case Examples

This chapter presents five case examples of post-tensioned bridge repairs and related maintenance actions performed by five different public agencies. An attempt was made to gather case examples from a diverse representation of states from different geographic areas. The participating agencies were the Florida Department of Transportation, South Carolina Department of Transportation, Ohio Department of Transportation, Virginia Department of Transportation, and the City of Minneapolis Department of Public Works. The case examples presented in this chapter were solicited from agencies through the survey and through personal contacts of the authors and NCHRP project panel. Interviews were conducted March–July 2020.

Case 1: Wonderwood Connector Bridge

The Wonderwood Connector Bridge is a 0.7-mile-long post-tensioned I-girder structure that was initially built from 2002 to 2004 for a cost of $36.5 million (see Figure 22). It is located northeast of Jacksonville, Florida, and serves as State Route 116 over the Intracoastal Waterway. It is a critical portion of the Wonderwood Connector, a $140 million project connecting Highway 9A to Mayport, Florida. The bridge opened to the public on July 24, 2004.

The structure has a 90 ft 9 in. wide bridge deck, serves both directions of traffic, and is supported by eight lines of drop-in I-girders. Each girder has four bonded, internal tendons with 15 to 19 prestressing strands per tendon. Each tendon has a corrugated metal duct and was injected with a proprietary grout. The bridge is currently undergoing extensive repairs following a series of inspections that revealed some tendon corrosion and severe grouting issues.

Construction

Several issues with the grouting operations were noted during construction but they were not immediately addressed. The main area of concern was a spliced, three-span, continuous, 644-ft-long section over piers 9 through 12 at the bridge's high point. The initial design did not provide enough vertical clearance to receive a Coast Guard navigation channel permit, requiring a major mid-construction design change. To facilitate the design change, counterweights were added in the side spans near the haunch segments over piers 10 and 11, and additional post-tensioning strands were added to some tendons. The tendon ducts had originally been sized for 15 strands, but to accommodate the counterweights, some ducts were installed with 18 to 19 strands. As a result, some tendons may have experienced restricted grout flow that contributed to the grouting problems detailed in the following section. Grouting operation reports detailed problems including grout cap and hose blow out, leaking grout, anchor head cracking, grout set, and grouting performed from both ends. Post-grouting inspections also noted sections of soft grout. At the time of construction, no remediative efforts were undertaken to address the soft grout.

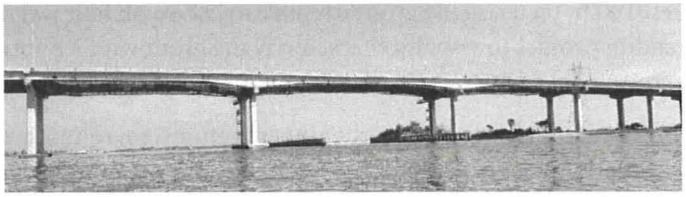


Photo credit: Kregg Diemer.

Figure 22. Charles E. Bennett Wonderwood Connector Bridge.

Grout Inspections

Subsequent to identifying chloride intrusion problems in tendons in other bridges using the same grout, the bridge owner ordered an invasive inspection of a limited number of PT tendons to obtain some grout samples and to assess the tendons for corrosion. The initial investigation was conducted April–May 2012. Five grout caps were inspected and found to have satisfactory grout. After chipping away the grout to reveal the anchorage, very limited surface corrosion was found on the anchorage, wedges, and strands. Following the grout cap inspections, four excavations were conducted along girder 8 between piers 10 and 11 to inspect the galvanized steel duct and tendon grout condition. This section is the haunch and drop-in segment that required the structural modification to add strands. All four of the exposed metal ducts had one or more perforations from corrosion in the top of the duct. A portion of the duct was removed, and grout samples were drilled out of the tendons for chloride analysis and visual characterization. Three of the four exposed tendons had a layer of putty-like grout, and all four had a layer of soft, chalky grout with normal hard grout underneath. Each excavation was repaired according to FDOT repair specifications.

On the discovery of corroded ducts and soft grout, the bridge owner initiated a second investigation to develop a better understanding of the corrosion issues. The inspection was conducted July–August 2012. The corrugated metal duct was exposed in an additional 32 locations throughout the haunch and drop-in segments, and at least one excavation was performed in each girder. Of the 32 excavations, 16 exposed ducts had some degree of corrosion. Of those 16 ducts with corrosion, eight had severe corrosion. Fourteen of the excavation sites had hard grout throughout the duct. The rest had some combination of hard grout, putty grout, an unidentified black material, and soft chalky grout. Upon grout removal, the condition of the post-tensioning tendons was also inspected. No corrosion was observed on the strands at 17 of the excavation sites. Minor corrosion was noted at 13 locations, and moderate and severe corrosion were noted at one location each. Much of the investigation was focused on the haunch segments, where the worst duct corrosion and grout conditions were found. Chloride analysis on the grout samples taken showed a chloride content of 0.01% to 0.04% by mass of cement, which is below the specification limit of 0.08%. In some locations, grout was found to have moisture contents of 50% to 75%.

Comprehensive Tendon Investigation

Following the findings of the two initial investigations, the bridge owner ordered a comprehensive, systematic inspection of every tendon to coordinate a repair strategy. A consultant specializing in nondestructive/minimally invasive inspection was contracted to perform the evaluation.

Investigation of every tendon was conducted from September through October 2014. Ground penetrating radar was used to identify the tendon profiles, and impact echo was used to identify

grout irregularities. To characterize the grout irregularity, 87 small holes were drilled at various locations in the tendon profiles to visually characterize the grout with a borescope. The location and type of each grout irregularity was documented to coordinate a repair strategy.

The study confirmed the findings of the earlier investigations, revealing large sections of voids and soft grout. One tendon was discovered to have a 20-foot-long void filled with water, attributed to bleed water left from construction grouting operations. Overall, 3% of the 13,555 feet of tendons surveyed had voids or soft grout. Only 30% had completely hard grout, and 67% had a combination of soft and hard grout. The prevalence of the deficient grout in the tendons instigated an extensive repair response.

Repair Strategy

Following the report from the comprehensive tendon investigation, the bridge owner contracted a consultant to develop a repair strategy. The consultant studied the bridge's history from the construction documents, as-built plans, and inspection reports. From these plans, the engineers computed time-dependent stresses to develop the ultimate and service capacity for the bridge assuming no structural irregularities. They then proceeded to evaluate the effects on ultimate and service limits of four tendon failure scenarios.

On the basis of the inspection report, the bridge owner adopted a multiphase repair strategy. The first phase had three goals to remediate existing grout problems:

1. Remove the sections of soft grout.
2. Fill voids with new grout using vacuum grouting.
3. Use an impregnation repair method to provide supplementary corrosion protection.

The second repair phase proposed adding additional external tendons to the bridge element to ensure that the bridge girders maintain the required prestress and ensure safety.

To accomplish Phase 1, the FDOT initiated a research study, conducted by researchers at the University of Florida, to evaluate the best methodology for grout remediation (Torres and Potter 2020). Two methods of grout remediation were evaluated: hydro-demolition to remove soft grout, and grout drying to remediate soft grout without removal. To evaluate grout remediation approaches, a mockup tendon assembly was constructed with nineteen 0.6-inch diameter seven-wire low-relaxation strands in a 4-inch duct. The duct was filled with alternating types of hard and soft grout. For hydro-demolition, inlet and outlet holes were cored into the side of the duct. Then a high-pressure water jet was used to blast the grout surrounding the inlet hole. After clearing the inlet area of grout, a high-pressure water tube was inserted into the hole and fed along the length of the tendon to blast the deficient grout and attempt to remove it from the duct. The study found that hydro-demolition was not effective at removing deficient grout.

The study also assessed a method of drying the grout to remove residual moisture in the tendons. Tendon laboratory mock-ups were constructed using layers of soft and hardened grout to simulate the tendons found in the bridge. Dehumidified air was pumped through the tendon to remove moisture from the grout until the relative humidity of grout at the air outlet reached equilibrium with the input air (see Figure 23). Although the methodology proposed effectively dried the grout, the use of atmospheric air caused corrosion of the prestressing steel. Thus, it was recommended to use the grout-drying technique in conjunction with a corrosion inhibitor. As a result of the research project report, FDOT modified the proposed repair strategy to include grout drying instead of grout removal.

Phase 1 repairs began in September 2017. The repair was planned as a staged effort and was completed in the summer of 2019. In the first stage, all grout voids were filled using

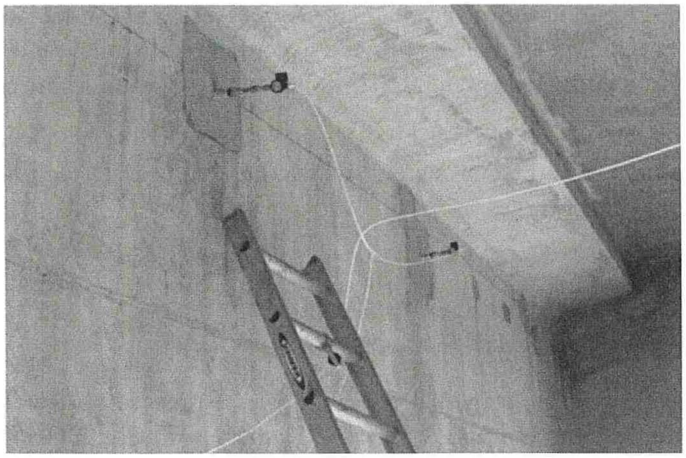


Photo credit: Florida DOT.

Figure 23. Grout drying.

vacuum-assisted grouting. Stage two consisted of the grout-drying process. Grout drying began in July 2018 and continued through January 2019. The criteria for acceptance for drying of the soft grout was set as either the relative humidity from the outlet ports had reached 20% or the moisture content of a sample of soft grout taken from the tendon was 40% or less. The dried air flowed from the center of the span outwards to minimize leakage and maintain air flow throughout the length of the tendon. Air flow rate, air temperature, and relative humidity at the inlet and outlet were monitored throughout the drying process (see Figure 23). During grout drying, while the contractor was obtaining a grout sample to determine the moisture content, a failed strand due to corrosion was discovered in one of the tendons. The discovery of the failed strand validated the decision to include supplementary post-tensioning tendons in Phase 2 repairs. Following grout drying, PT tendons were impregnated with a proprietary corrosion inhibitor—a hydrocarbon and silicon polymer product.

Phase 2 is in progress and involves the addition of supplementary external tendons and post-tensioning bars to ensure public safety and longevity of the bridge. A consultant performed the structural analysis to determine the prestressing parameters—a challenge because the bridge already had post-tensioning and is considered structurally indeterminate. The analysis was conducted using various scenarios of tendon failure. It was determined that two tendons would need to be added to each bridge girder. Post-tensioning bars will be added at diaphragms added between the girders at critical locations along the beam profile to ensure the additional prestressing will not exceed the capacity of the bridge. Phase 2 repairs were expected to begin in summer 2019 and continue through May 2020. Repairs are projected to cost $7.2 million.

Summary

Grouting problems noted during construction may have been the result of late design changes made to add strands to existing ducts, creating strand congestion inside the tendon. Following discoveries of soft grout and tendon issues in similar structures, investigations revealed extensive soft grout and tendon corrosion that could lead to tendon loss. To rehabilitate the bridge, the owner

- Conducted extensive nondestructive testing to accurately define the bridge's deficiencies and coordinate a repair strategy,
- Relied on significant structural analysis to inform repair decisions,

- Commissioned a research study to evaluate efficacy and feasibility of available repair methods,
- Added additional external tendons to provide structural redundancy, and
- Performed grout remediation and tendon impregnation to inhibit future corrosion.

Overall, the project was a large collaborative effort between the bridge owner, consulting engineers, researchers, and the contractors to effectively remediate tendon corrosion in the Wonderwood Connector Bridge.

Case 2: James B. Edwards Bridge: I-526 over the Wando River

The I-526 bridges over the Wando River are a pair of precast, post-tensioned box-girder structures spanning between Mount Pleasant and Daniel Island, South Carolina. Construction of the structures occurred in 1985–1989. The structures were officially opened to public traffic in 1991, after a period of relative non-use during which they had served as access for another construction project. The structures are owned by the South Carolina Department of Transportation (SCDOT).

The eastbound and westbound structures are separate twin structures running parallel to each other for a total abutment-to-abutment length of 7,900 feet. Each structure consists of two symmetrical approach spans—constructed as span-by-span—flanking a main span unit constructed using the balanced cantilever method. Each structure contains 92 tendons—eight accessible, external tendons and 84 internal tendons.

A unique pair of structures in the state of South Carolina at the time of construction, the Wando River bridges remain the only post-tensioned box-girder structures in the state's bridge inventory. There existed little or no in-house post-tensioning expertise at the time—commonplace during this period when post-tensioned structures were still relatively rare and were beginning to be built around the country.

Issues encountered in these structures and described in this case example include tendon ruptures (westbound structure), voids in the filler material (eastbound structure), issues with tendon encapsulation and detailing (both structures), and water intrusion (both structures).

Construction records and as-built plans for the structures are incomplete or do not exist, further complicating the agency's ability to respond to issues. Efforts have been undertaken over the years to develop as-built records for the structures, which have been noted as observably different from the remaining construction plans.

Construction and Early Structure Life

In response to public concern regarding alleged poor construction practice by the prime contractor, a state-mandated investigation was undertaken in the 1980s. The investigation found no evidence warranting concern. This effort, however, provided an early review of constitutive materials and construction practices.

The general superstructure condition was noted as good in internally conducted inspections during the early 2000s. Inspections during this period reported evidence of efflorescence, map cracking, some holes in the post-tensioning duct, minor diaphragm and deviator cracking, and some vertical cracking. Extensive deck patching was conducted to address spalling with exposed rebar. No major issues of concern specific to the PT system were noted as requiring address. A repeatedly documented issue was the presence of "pigeon droppings" inside the box that were vacuumed out. A summary of inspection reports from this period describes routine inspection

findings as containing "limited information due to form only and no corresponding report" (South Carolina Department of Transportation 2018).

In 2006, some issues of concern were noted in an inspection of the westbound structure. In addition to fine spalling and map cracking, the following observations were made:

- A PT block was exhibiting "crushing."
- Heavy spalling and patching work existed on the underside of two spans.
- Large cracks were documented at two spans, one near an expansion joint.

In-depth Investigations

An asset management contract was initiated in 2010, which began externally managed inspections. Significant water intrusion (running water) into the superstructure during rain events was observed during this period.

In August 2010, the first indication of tendon corrosion was noted during a walk-through inspection of both structures. The following items were inspected during this walk-through: external HDPE tendons, anchorage pour backs (PT pour backs), HDPE duct couplers, HDPE duct and diaphragm connections, HDPE duct and deviator connections, grout vents and ports, segment joints, and other components pertinent to the PT system (Theryo 2010). Several issues of concern were noted, including small openings of approximately 1 inch in diameter in many external tendons' HDPE duct (Figure 24); evidence of uncontrolled grout flow during construction (Figure 25); inadequate corrosion protection of the tendons (Figure 26); geometry conflicts; improper vent connections (Figure 27); and evidence of corrosion at exposed PT bar anchorages (Figure 28). Of particular interest, the inspection team noted white, sometimes wet, material depositing at several locations along the external tendons and appearing to come out of the HDPE duct (Figure 29). These white deposits were noted along free lengths of the duct, at duct couplers, and at pour backs. All of the documented issues were found to occur in both eastbound and westbound structures.

Additional routine inspections were performed on both structures on May 28, 2010; at this time, the structures were approximately 21 years old. The first suspicion of a possible loss of tendon force was noted in this inspection report, citing leakage and spalling in one pier of the eastbound structure, though poor joint material/installation was also a provided potential cause. No tendon loss was observed in the eastbound structure (Theryo 2010).

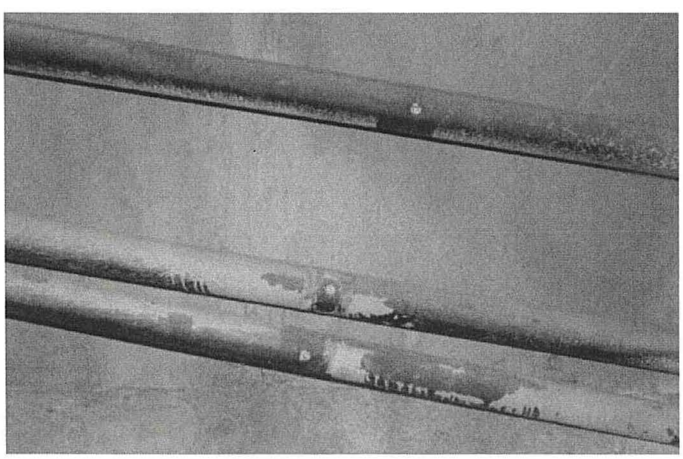


Photo credit: Parsons Brinckerhoff.

Figure 24. Holes in ducts in free length, assumed to be former grout ports.

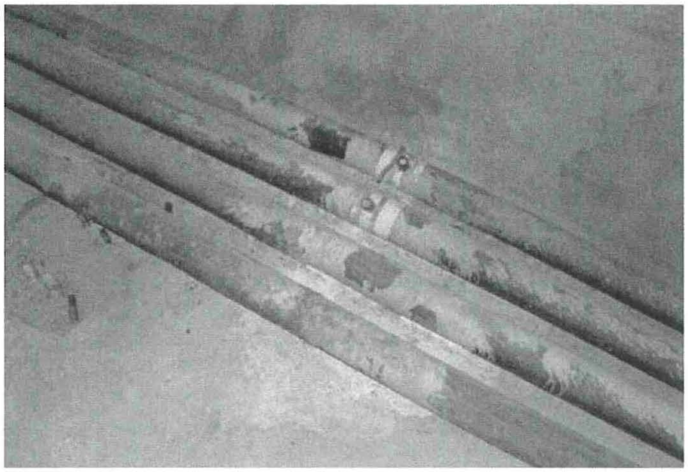


Photo credit: Parsons Brinckerhoff.

Figure 25. Evidence of leaking grout during construction.

Photo credit: Parsons Brinckerhoff.

Figure 26. Nonstandard covering of tendon.

Photo credit: Parsons Brinckerhoff.

Figure 27. Improper vent connections.

Photo credit: Parsons Brinckerhoff.

Figure 28. PT bars with corrosion.

In light of these findings, a special in-depth, preliminary investigation was undertaken of the external tendons in both the eastbound and westbound structures (October 2011 Preliminary External Tendon Final Report). Inspections included laboratory analysis of samples taken from the structure, including chemical, petrographic, chloride, and water analysis. The investigation findings were multifold:

- Testing of the white formations identified the substance as composed of principally calcium carbonate, suggesting that these formations occurred after water had infiltrated the post-tensioning system and leaked out at certain locations. As the water evaporated at the leak points, deposits of calcium carbonate remained in the form of stalagmites and stalactites. The formation of such accumulations likely took many years.
- Ongoing water leakage was observed at several locations. In one case, a source of water infiltration was identified as an improperly filled, deck-level grout vent tube. The report suggested that "many more grout vent tubes [were] not completely filled with grout (or perhaps the grout had degraded) extending directly to the top surface of the deck." This could provide a direct pathway for air, water, and contaminant (including chlorides from known use of deicing salts) intrusion.

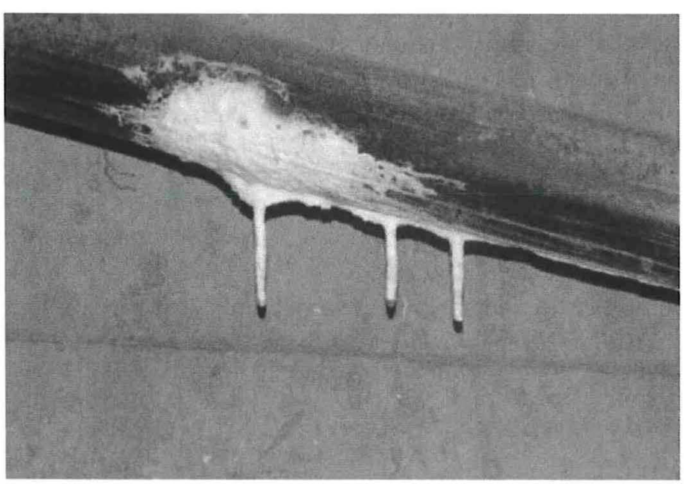


Photo credit: Parsons Brinckerhoff.

Figure 29. White deposits at multiple locations.

Actions were taken in 2012–2013 to identify water penetration pathways and to address water intrusion, including injection of improperly filled vent ports, partial depth penetration patches to the deck, and application of methacrylate coating to the top of the deck. Attempts (multiple over the life of the bridge) to identify and address water intrusion pathways have only been partially effective. Communication (of air, water, contaminants, for example) between tendons remains an ongoing issue, with water penetration of the structure still occurring.

Extensive nighttime inspections revealed hundreds of improperly constructed vent locations. Inspections to identify vents in need of address were difficult. In some cases, it was not easy to distinguish between polished aggregate and a vent location in need of remediation. And in some cases, vents permitted clear transmission from the deck level to tendon ducts(s). In visual inspections made with a borescope, sunlight and traffic were identifiable through vents that had not been fully grouted and sealed. In other cases, vents were found to contain poor-quality grout; it was suspected that improper grouting practices (i.e., not waiting until uniform consistency grout was outflowing before closing the vent), were used (M. K. Turner, interview, 2020).

Incident 1: Tendon Rupture

In 2016, a tendon rupture occurred in tendon "M1" of the westbound bridge. Analytical checks were performed, and a truck acceleration lane was closed, maintaining the two primary traffic lanes during the subsequent repair. SCDOT consulted with post-tensioning experts in both private firms and public agencies, including the Florida DOT, to inform its response to the situation.

Hydro-demolition was performed to remove the tendon from the box girder. The damaged tendon was salvaged for inspection and testing. Corrosion of the M1 was evident, with pencil-point reductions apparent in some wires of the prestressing strand. Inspection of the grout within the tendon found some sections with visually observable, multiple colors, leading the agency to believe that some carbonation had occurred.

The M1 tendon was replaced. Repairs took approximately four months to complete and cost approximately $1.8 million (Hall 2018). A replacement tendon was inserted in the same location, tensioned, and filled with a proprietary thixotropic nonshrink grout. The replacement tendon was installed to vent into the inside of the box girder in an effort to protect the new vents by using the physical barrier of the structure itself.

Several testing and inspection efforts were undertaken to assess bridge health, including magnetic flux, corrosion potential testing, extensive borescope inspection, and destructive inspections during which tendons were cut open for assessment. An estimated 12 to 14 miles of tendon free lengths were inspected through various means. Inspections recorded voids, evidence of poor-quality grout, and other issues of concern.

In September 2017, testing was conducted on the external tendons in the main spans of both the eastbound and westbound structures. Testing was conducted on all seven of the original tendons in the main span of the westbound structure. The eighth tendon was not tested because it had just been replaced earlier that year. On the basis of preliminary information, corrosion was found on two of the seven tendons of the westbound structure. When testing was nearly complete, a second tendon failure was identified (Hall 2018).

Incident 2: Tendon Failure

On May 14, 2018, a second tendon failure was identified during a weekly bridge inspection; the time of the tendon failure remains unknown. The weekly inspections—initiated in response

to the rupture of M1—included monitoring of the M4 tendon; this monitoring was important in identifying the tendon loss because no other indication had revealed its occurrence. The inspector observed the tendon move a noticeable, unexpected amount under manual excitation by the inspector.

Both the M1 tendon that ruptured in October 2016 and the May 2018 M4 tendon failure occurred at the 7-foot-thick concrete diaphragm that the tendon passes through between the individual box girders. The response upon discovering the second failed tendon was immediate and included in-depth inspection, structural analysis checks, replacement of the affected tendon, and installation of redundancy tendons.

Initial efforts to identify the cause of the tendon failure did not identify an obvious cause. An attempt to borescope the tendon had only limited success, encountering a blockage assumed to be grout. The tendon was drilled within 6 in. of the failure location, but no conclusions could be drawn. Slight evidence of corrosion was found; it remained unclear if this was the only mechanism affecting the tendon. Given the uncertainty, the agency elected to close the impacted structure to traffic to ensure the public's safety.

The affected tendon was replaced, tensioned, and grouted. In addition, two additional, supplementary tendons—initially detailed for the addition of future lanes—were installed for redundancy, with requisite analysis checks performed.

Technical support was provided by multiple outfits to investigate issues, address concerns, provide on-site support, and ensure safety prior to the bridge reopening. Supporting entities included FHWA South Carolina Division staff; FHWA structural engineering specialists deployed from Washington, D.C.; consultants with experience in evaluating PT issues; and staff from other state departments of transportation.

Summary

Following circumspect reviews of documentation in investigations subsequent to the second tendon failure in 2018, it was noted that these bridges had been "problematic almost from the beginning, especially with regards to water intrusion" (Hall 2018), a finding at the time consistent with other states' reported issues with similar structures (from Hall 2018).

The agency's general approach to addressing issues with this structure has been multifold. In the absence, in some instances, of identifiable causes, the approach has focused on

- Significant structural analysis,
- Development of additional structural redundancy, and
- Development and deployment of a rapid repair framework in-system, installed and ready to respond.

Case 3: Veterans' Glass Skyway

Owned and maintained by the Ohio Department of Transportation (ODOT), the Veterans' Glass City Skyway (Figure 30) over the Maumee River in Toledo, Ohio, serves as a critical section of I-280. Built in 2002–2007 at a total project cost of $237 million, it was the largest project undertaken at the time by ODOT. Among the many innovative features incorporated into the bridge design, the bridge wearing surface was cast integrally into the bridge segments. The girder was cast with a 2-inch-thick integral wearing course and 2.5 inches of concrete clear cover.

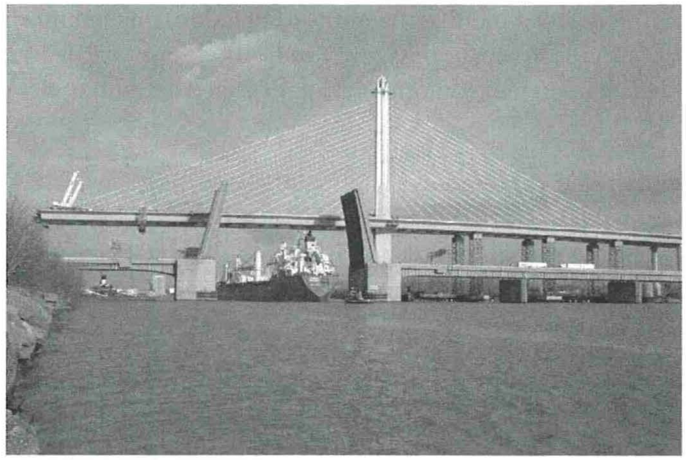


Photo credit: Ohio Department of Transportation.

Figure 30. Veterans' Glass Skyway.

Construction

During construction, two custom gantry cranes were used to facilitate the erection of each bridge span; each 150-ft span could be erected in approximately one week using the cranes. The cranes supported the spans during post-tensioning operations. On February 16, 2004, while erecting the 12th span, one crane fell, killing four workers and injuring four others. The failure and subsequent problems with the other gantry crane caused a 16-month pause in bridge construction, with ramifications to the post-tensioning operation. Because of the construction delay, many different shipments of Sika grout were used for post-tensioning operations. The bridge opened to the public June 24, 2007, one year after its scheduled opening.

Tendon Investigation

Following completion of construction, some of the grout used in the structure was identified by its manufacturer as potentially containing high chloride contents beyond the project specifications and the PTI guide specifications (limit of 0.08%). A technical memorandum, HIBT-1, issued by the Federal Highway Administration on November 23, 2011, identified 34 projects in 18 states affected by the manufacturer's product (Gee 2011).

In response, a 2012 study was conducted on the Veterans' Glass Skyway Bridge to evaluate the potential for elevated chloride levels in the PT tendons. As part of the investigation, 148 longitudinal external tendons were opened to sample for chloride content. Several tendons were found to contain acid-soluble chloride exceeding the 0.08% limit; the maximum identified content was 0.116% in some cases. Further inspection of the post-tensioning tendons found only one strand with minor surface corrosion, which could have possibly been present at installation. No extensive repairs were required.

Incident 1: Truck Fire Reveals Tendons

On November 6, 2015, a semitruck had a tire blow out and it caught fire after it struck a guard rail. The truck stopped near the midpoint of the bridge. The ensuing fire damaged the surrounding concrete, causing pop-outs and spalling of the deck. Approximately 100 feet of the concrete

deck underwent grinding in preparation for repair. Unexpectedly, grinding the deck exposed some of the post-tensioning ducts.

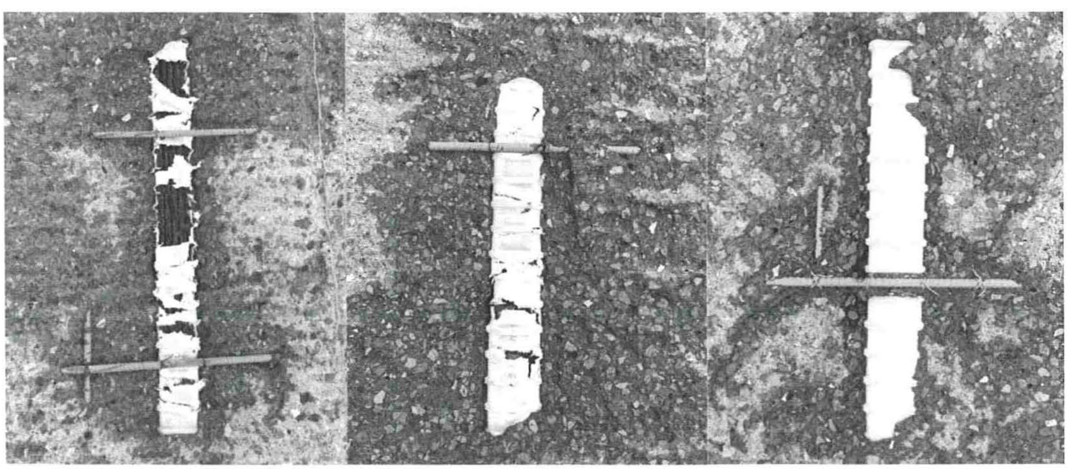
Response: Where the ducts were broken and exposed, the tendons were repaired by pressure washing out the remaining soft grout and replacing with epoxy. The wet epoxy was covered with sand, and the epoxy surface was to be scratched to provide an adequate bonding surface for the concrete deck pour.

Incident 2: Bridge Resurfacing

Resurfacing of the bridge was scheduled to occur in 2020; the project is ongoing. The project replaces the bridge deck by milling 1 inch off of the concrete overlay and hydro-demolishing the next ½ inch to provide a roughened surface for resurfacing. As the contractor attempted demolition, however, the process exposed transverse post-tensioning tendons in the top flange of the box girder in more than 70 locations. Because the ducts were specified to have at least 4.5 inches of cover, it is unclear exactly how the ducts were exposed by milling. Several ducts have been identified in the wrong locations.

Hydro-demolition has also broken open some of the ducts (see Figure 31). All locations where the ducts have been broken are coincident with voids or soft grout. Ducts filled with apparently good grout have not broken during hydro-demolition. It is hypothesized that the voids resulting from improper duct filling may be contributing to the duct damage during the hydro-demolition process.

Locations of duct damage are undergoing repair. Repair is a multistep process: water blasting to remove loose debris, epoxy to seal, sand to provide a rough surface, and a final concrete cover layer. Lacking an alternative method of removing the concrete deck, the bridge owner's milling, hydro-demolition, and repair approach is being employed for the entire bridge length where necessary. The repair strategy has led to concern that the bridge deck will have to be repaired again in 15 to 20 years. To facilitate later resurfacing and repair efforts, the bridge owner is cataloging thorough documentation of damage locations.



(a) (b) (c)

Photo credit: Ohio Department of Transportation.

Figure 31. Exposed tendons during resurfacing: (a) severely damaged, (b) moderately damaged, and (c) undamaged.

Summary

The Veterans' Glass Skyway in Toledo, Ohio, serves a critical section of I-280 over the Maumee River. It features several innovative design concepts and a significant amount of PT. The following are pertinent details related to the repair and maintenance actions for the PT system of this structure:

- Construction delays led to the use of a wide variety of grout batches and lots.
- An innovative integrally cast concrete slab minimized the clear cover over tendons in the top slab.
- Proactive invasive investigations revealed minimal chloride intrusion and corrosion in the tendons.
- Bridge deck resurfacing exposed tendons in the top slab and revealed areas of soft grout.
- The agency has developed a standard repair policy, although it will not prevent the issue from occurring in future repairs of this structure.

Case 4: Varina-Enon Bridge: I-295 over the James River

Owned and maintained by the Virginia Department of Transportation (VDOT), the Varina-Enon Bridge carries I-295 over the James River near Richmond, Virginia (see Figure 32). It was constructed in the late 1980s and opened to traffic in 1990. The structure is approximately 4,686 feet long with two approach spans flanking a main span. The main span, supported by cable-stayed pylons, is composed of two single-cell precast box girders connected by a precast delta frame to form one structural unit. Each of the approach spans is composed of two separate single-cell precast box girders, with each girder carrying one direction of traffic.

The specification at the time of construction called for a grout filler material for the post-tensioning tendons to be mixed on-site, composed of conventional cement, water, and expansive admixtures (Parsons Brinckerhoff 2010). Given the location and climate of the structure, the structure is expected to routinely experience moisture intrusion and condensation throughout its life (Parsons Brinckerhoff 2013).

Early Structure Life

Early inspections were conducted routinely and in accordance with NBIS requirements. Inspections in 2001 uncovered voids in a large quantity of tendons, identified primarily through

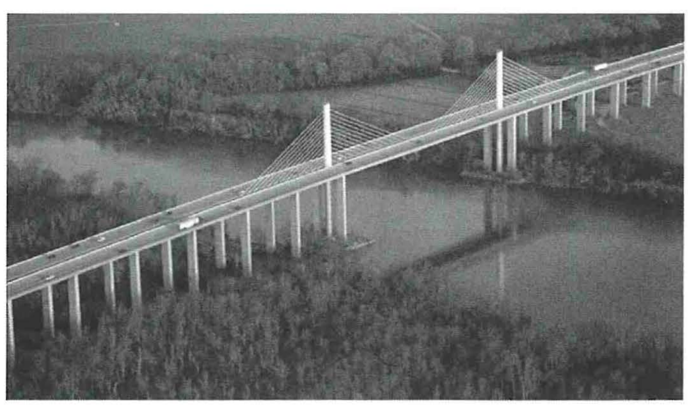


Photo credit: Virginia Department of Transportation.

Figure 32. Varina-Enon Bridge.

borescope inspection via vent tubes that had been incompletely filled with grout or that were completely empty. Evidence of bleed water and grout subsidence was noted. While it was unclear whether expansive grout materials (though permitted) were used by the contractor, later testing revealed the original grout material to be of poor quality, with a suspected high water-to-cement ratio beyond the maximum specified.

Two efforts in 2003 and 2004 were undertaken to fill identified voids via vacuum grouting, though only approximately 50% were accessible. Repairs were made with three different proprietary grouts.

A 2005 inspection identified one tendon "bent out of plane." A 2007 inspection identified one failed tendon and another tendon of concern. Additional inspection and hammer sounding of all accessible tendons was performed. An area of concern was identified where a drain plug had been blocked with grout during construction, allowing water to collect within the structure and to submerge a tendon in acid water. The duct of the adjacent tendon was opened, revealing corrosion. The tendon was carefully de-tensioned and replaced. A total of two tendons were replaced.

Of particular note, post-mortem inspections were performed on the removed tendons. In the failed tendon, corrosion was noted at the interface between the old grout material and the new material injected in 2003–2004. The use of dissimilar grouting materials was suspected of creating a macrocell corrosion site.

In 2007, a research effort with the University of Wisconsin used magnetic flux to inspect all of the longitudinal tendons. Section loss identified by magnetic flux was confirmed in two tendons. The locations with section loss were opened and the duct was replaced with transparent duct so further corrosion could be observed. Eight locations were visually monitored over time. The rate of corrosion appeared to be very low. Additional observations indicated worsening structural integrity, including advanced degradation of the deck wearing surface (perhaps influencing the structure's water-tightness), the presence of diagonal cracking in the girder webs, and significant cracking/separation at diaphragms and top deck.

Conditions and specific issues were observed to deteriorate between inspections in 2007 and 2010, with a number of issues identified with potential structural and durability implications to the post-tensioning system, including, in part

- Shifting of a box segment at one pier,
- Diagonal cracking in box segment webs,
- Suspected strand slippage in external tendons, and
- Suspected defects in additional tendons.

In-depth Inspection (2010)

These findings motivated the bridge owner, VDOT, to authorize an additional in-depth study by a consultant in 2010, to include recommendations for remediation. The intent of this effort was to provide expert opinion on a course of action on the basis of the existing inspection reports (primarily those from 2007 and 2010) and visual inspections of the identified critical deficiency items.

In a parallel effort in 2010, the Federal Highway Administration conducted testing at Varina-Enon in an early effort to use magnetic flux leakage (MFL)—a technique evaluated for its effectiveness at the Turner Fairbank Highway Research Center in early 1990—to evaluate in a nondestructive manner the external tendons inside the box girders for evidence of defect. Locations of suspected defect were cut open for additional testing and inspection, grout defects

Photo credit: Parsons Brinckerhoff.

Figure 33. Repair connection and coupler at diaphragm.

were repaired, and the duct was resealed with heat-shrink sleeves. The bridge owner is positive of the efficacy of MFL as a defect detection technique, commenting that all identified locations by MFL did reveal defect. The possibility of defects not detected by MFL was not evaluated.

Inspectors noted that the external tendons were in fairly good condition, though there was evidence of PT duct connection repair occurring both during and after construction (see Figure 33 and Figure 34). The connection repairs also exhibited evidence of grout leaking during its injection, which may have necessitated the repairs in the first place. Unlike current standard practice, the inspectors noted that most of the duct couplers were not waterproof. Inspectors surmised that grout leaking during construction may be associated with void presence in the hardened grout. It is important to note that connections between lengths of HDPE duct have been greatly improved and standardized since this time.

Inspectors noted that several strands had been exposed and exhibited some corrosion. In addition, some tendons contained a length of clear duct material, allowing direct observation of the tendon's strands and evident strand corrosion (see Figure 35).

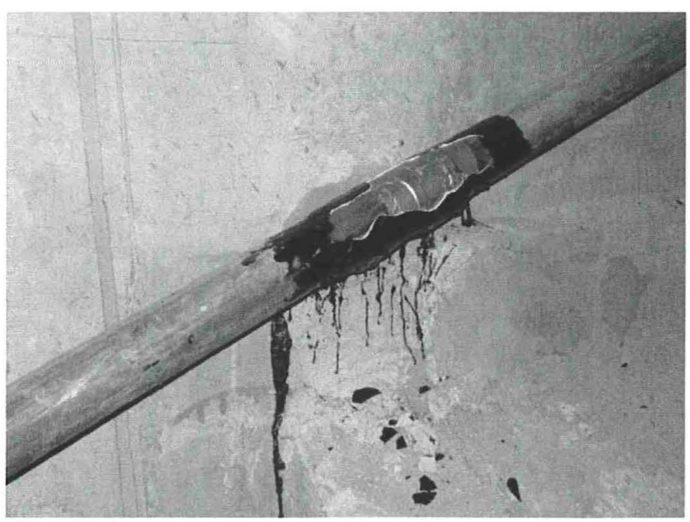


Photo credit: Parsons Brinckerhoff.

Figure 34. Mid-length repaired tendon coupler.

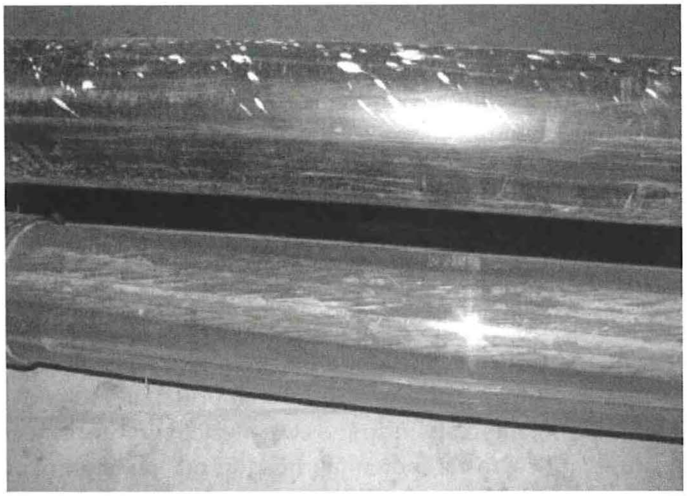


Photo credit: Parsons Brinckerhoff.

Figure 35. Clear duct for tendon observation.

Several tendons had been identified in the first 2010 inspection report as suspected of slip; these tendons had been suspected because of changes in the repair material, with an evident change in a crack width in the epoxy coating the connection, between inspections occurring in 2007 and 2010.

These tendons were carefully inspected during the subsequent in-depth inspection, but slippage could not be verified as the cause by inspecting the tendon mid-length because the crack in the repair material could have been caused by thermal changes within the structure. Inspection of the anchor (and wedges) and the trumpet was recommended.

Though not inspected because of access issues, the vertical tendons were indicated as important for later consideration, given that the older generation of grout was likely used at the time of their construction, and given evidence of excessive bleed water in such tendons with these materials.

Box Girder Cracking

Structural member cracking of box-girder webs and diaphragms was also inspected in 2010. The structure contains two types of diaphragms over the piers:

1. Diaphragms over sliding bearings, and
2. Diaphragms integrally connected to the pier (with PT bars).

The inspection report concluded that there existed no evidence that unwanted movement of the bridge structure had compromised structural integrity, but it recommended repair of the external tendon connections, as well as restoration of the corrosion protection system. No direct evidence of water intrusion or deficient grout was noted during this inspection (*Varina-Enon Bridge I-295 over James River Final Report: Stage I Study Report for Evaluation of Bridge Deficiencies and Recommendations* 2010).

In-depth Investigation (2012)

Grout voids, corrosion, and wire breaks observed and documented in regular and in-depth inspections from 1999 to 2012 triggered an additional assessment of the post-tensioning system. A field evaluation was performed in 2012 by Parsons Brinckerhoff, in collaboration with an

NDE and corrosion specialist, Siva Corrosion Services, Inc., to assess the grout and prestressing strand in the external tendons and the vertical tendons.

The evaluation examined 13 external tendon locations and 18 vertical PT bars. The inspected locations represent only a handful of the total 480 external tendons and 360 PT bars in the structure and were selected on the basis of previous inspections. Test locations were selected by VDOT on the basis of their perceived corrosion risk, focusing on external tendon high points and PT bar tendons in which the grout vent tubes were observed to be empty.

External tendons were manually opened, removing the plastic duct at test locations. The conditions of the grout and strand were observed, noting section loss or wire breaks, if any. With the tendon open, the team performed field tests on the grout for resistivity and alkalinity. Samples were gathered for later laboratory testing of moisture, chloride, sulfate, and gypsum contents, as well as petrographic assessment. Exposed strands were tested for rate of corrosion (via polarization resistance testing) and corrosion potential. In addition, evidence of corrosion was noted using the PTI corrosion classifications, observed by visual means. PT bars were inspected via the open grout vent tubes using a borescope. The general condition of the grout, including the presence of voids, was documented and water samples were taken, if applicable.

At all but two external tendon locations, the strands were observed to have Class 2 corrosion (by visual classification), or light surface rust. In one location, a tendon was observed to have one broken wire (see Figure 36); another location contained four broken wires (Figure 37). Section loss was also exhibited by adjacent wires in both locations. These two locations were the same locations where broken wires had been identified in a 2007 National Transportation Research Center visual survey; since 2007, the number of broken wires and the percentage of section loss had progressed (Parsons Brinckerhoff 2013).

In general, the rate of corrosion testing for the strands, however, did not corroborate visual findings. These tests assessed the corrosion rates for tested tendons to be between low to moderate, with greatest corrosion damage encountered in the tendons with the highest moisture content. Rate of corrosion testing via polarization resistance testing has some limitations that are important to keep in mind. The test can only determine the rate of corrosion for strands embedded in grout. Strands that are uncovered or exposed because of a grout void with obvious section loss (such as those encountered in the Varina-Enon Bridge), cannot be evaluated with this method. Also, corrosion potentials were measured, but these also provided no corroborating evidence to suggest active corrosion. The tendons have not been replaced.

Photo credit: Parsons Brinckerhoff.

Figure 36. One broken wire and heavy section loss.

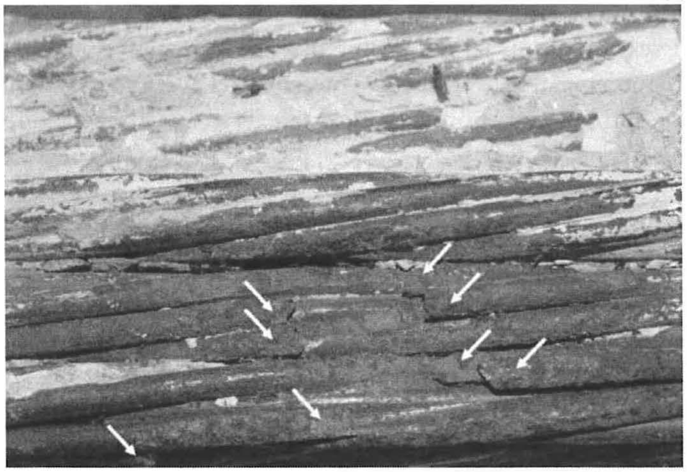


Photo credit: Parsons Brinckerhoff.

Figure 37. Four broken wires and heavy section loss.

Considering the multitude of evaluation methods used to assess the grout, the quality of the grout tested in this inspection was generally good. Though no strands were found to be embedded in such locations, grout near the top of the duct was found to be visually poor (white and chalky) and to exhibit lower than desirable pH.

Since 2012

Additional maintenance, repair, and inspection efforts have been performed by the bridge owner since 2012 to address a handful of concerns and to facilitate assessment of the structure's integrity. Hairline and map cracking has recently been identified in the grout pour backs on the transverse PT in the deck. No information is available regarding the surface preparation or pour-back materials used in these details.

During a regular bridge safety inspection, an external transverse PT tendon, part of the delta frame, was found ejected from the structure. Further inspection revealed that this tendon had never been grouted. The tendon was replaced. This finding precipitated an increase in inspection frequency. An additional inspection was undertaken of the transverse and vertical tendons. Access to vertical tendons was not always possible; of those inspected, approximately 80% of the vertical tendons were found to have a void of the top 8 ft of the tendon. A wire break was also found. The field work for this inspection concluded in 2019. The agency is currently developing its response.

Considering the structure's long history of issues, the bridge owner has taken several actions to facilitate monitoring. These actions include increased inspection frequency of greater scrutiny, installation of monitoring instrumentation and supplementary equipment, and the categorization and management of the Varina-Enon as a "special structure." In 2013, VDOT installed interior lighting in boxes throughout each span. Although this has no direct effect on the PT system, the agency is largely positive on the effort, citing that it has greatly helped with subsequent inspection efforts. In 2014, four of the tendons with monitoring locations were impregnated with a corrosion inhibiting liquid and the monitoring was discontinued. The FHWA magnetic flux monitoring occurred several times after 2014. In 2018, in response to concrete cracking in the pylons, additional PT was installed, using flexible filler materials.

VDOT has implemented a long-term monitoring plan with researchers at Virginia Tech, with instrumentation to gather information on thermal effects and effective prestressing.

The effort is expected to wrap up in 2021 and will assist in both improving the accuracy of load-rating and assessing the structures' durability. Additional efforts, including investment in an acoustic emissions system, and further measurements using magnetic flux leakage are anticipated to be used in conjunction with these efforts to assist the agency's future decision making. Inspection frequency has been increased. Regular inspections occur every 2 years, with hands-on, in-depth inspections occurring every 4 years. Baseline data on the structure's vibration characteristics and geometry, including pylon elevations, are currently being gathered to facilitate later assessment.

Summary

The Varina-Enon Bridge near Richmond, Virginia, has undergone two external tendon replacements in the past 20 years. Attempts to use nondestructive methods (corrosion potential, rate of corrosion) of tendon assessment were not successful in confirming known tendon corrosion issues. Testing grout quality at isolated test locations found the grout quality to be good, and the cause of the tendon corrosion could not be attributed to the grout itself. Instead, locations of identified strand corrosion and wire breaks were all in areas of voided grout. VDOT completed the following efforts to preserve the structure:

- Vacuumed grouted grout voids, but noted grout discontinuities could contribute to the formation of macrocell corrosion.
- De-tensioned and replaced multiple broken tendons.
- Successfully used the magnetic flux leakage method of NDE.
- Increased visual and in-depth bridge inspection frequency.
- Installed instrumentation to monitor the structure's condition.
- Designated the structure as a Special Structure to ensure long-term surveillance.

Case 5: Plymouth Avenue Bridge

Owned and maintained by the City of Minneapolis Public Works Department, the Plymouth Avenue Bridge crosses the Mississippi River in downtown Minneapolis, Minnesota. Opened in 1983, the bridge is a 934-ft-long pair of post-tensioned segmental structures. Four lanes of traffic are carried by parallel, single-cell, concrete box girders in two directions, westbound and eastbound. Cast-in-place, the main span was constructed with form travelers and cantilever construction; the two approach spans were cast-in-place on falsework.

In-depth Inspection (2010)

Biennial inspections were performed regularly on the Plymouth Avenue Bridge from its opening in 1983 to 2008. During this period, inspectors did not note anything to trigger an in-depth inspection. In 2010, an inspector walking through the interior of the segmental box noticed light penetrating the interior of the box, emanating from the bottom slab of the box. With manual effort and a heavy rod, the inspector was able to remove large chunks of concrete, revealing heavily corroded tendons (Figure 38).

Subsequent inspections conducted in 2010 revealed five heavily corroded tendons in one span of the eastbound structure. The identified tendons were located in the bottom slab concrete of the box adjacent to drains (Figure 39). At least two of the identified tendons were found to have lost all prestressing force. Further examination revealed that water had been penetrating the interior of the box for many years.

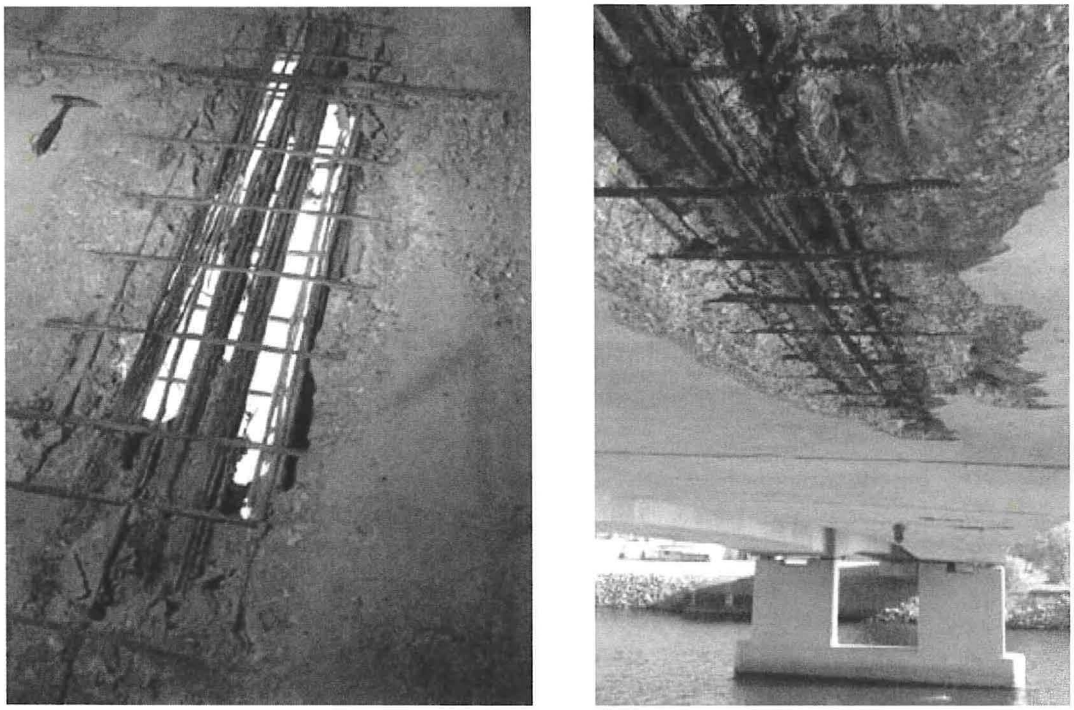


Photo credit: Corven Engineering.

Figure 38. Corroded bottom slab tendons identified in initial inspection.

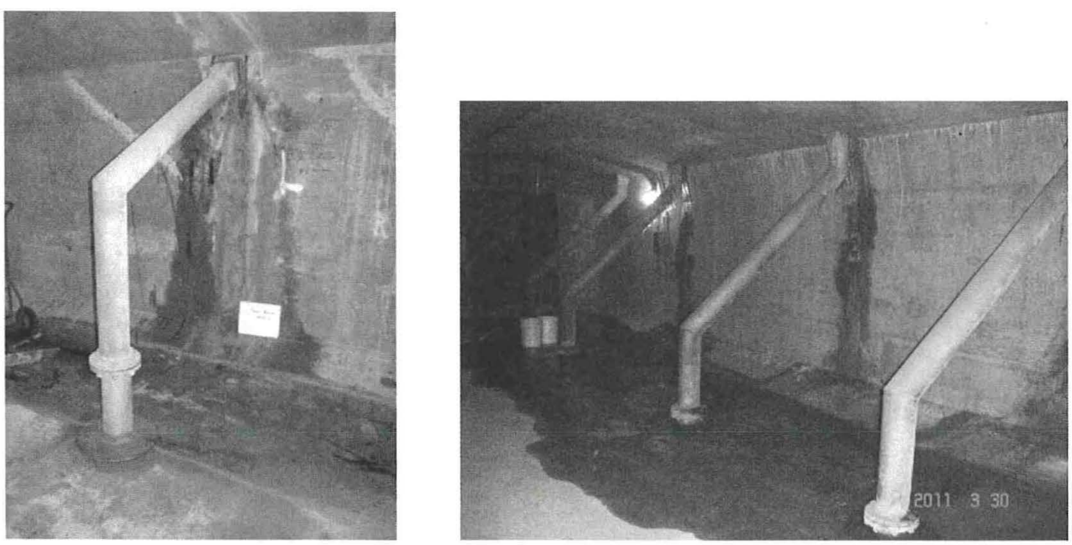


Photo credit: Corven Engineering.

Figure 39. Evident water intrusion around drainage system.

Subsequent in-depth inspections were conducted by a consultant; the inspection aimed to further visually inspect, with invasive techniques. The following were targeted for this in-depth inspection:

- Previously identified, corroded tendons,
- Continuity tendons in the bottom slab haunch in the same general vicinity,
- Continuity and draped tendons in the same general vicinity of the bridge,
- Selected cantilever tendons, and
- Selected anchorages of the bottom slab continuity tendons.

In-depth invasive inspections involved careful drilling through the concrete superstructure at assumed tendon locations for visual inspection. Observation was made of the galvanized duct condition, relative grout fill in the tendon, grout condition, and the appearance of the prestressing strand. Damage in localized regions was severe (complete PT loss in Span 3) to moderate (wire breaks in other locations). In areas adjacent to regions of damage, grout appeared to fill the ducts and be of good quality, and galvanized ducts and prestressing strand did not exhibit corrosion.

Invasive inspection of selected anchorages was performed on bottom slab continuity tendons; the two pour backs selected for this investigation were chosen on the basis of observed signs of potential distress (see Figure 40). One pour back had exposed rusting reinforcement (Span 3 westbound), one pour back had observable water staining (Span 3 eastbound). Pour backs were removed with pneumatic air hammers. Grout vents in the anchorages were drilled as far as geometrically possible; grout appeared to fill the anchor. Despite the presence of water, the Span 3 eastbound anchorage was in good condition, with what was assumed to be a thin epoxy coating more than 85% of the anchorage; a light surface rust was observed on the remainder of the anchorage. The Span 3 westbound anchorage was covered in a heavier rust on the wedge and anchorage plate, but no deep pitting or section loss was noted (Corven Engineering 2010).

Damage was attributed to a long period of wet/dry cycling, during which run-off and wind-blown water from the drainage system saturated the lower slab of the box girders. The presence of moisture, combined with seasonal freeze/thaw, caused local cracking and spalling of the concrete, eventually allowing exposure of the post-tensioning tendons in the box girders' bottom slab. Significant damage was identified by the inspections, mainly in Span 3; tendons in this span were found to have lost all post-tensioning force.

Photo credit: Corven Engineering.

Figure 40. Exposed bottom slab continuity tendon anchorages.

Less severe damage was identified in adjacent spans; wire breaks were identified, but force was found to have been recovered at some distance from the breakage through friction and grout interlock. Identified damage was severe enough to require bridge closure until the conclusion of the repairs (and the satisfaction of the engineer). Repair recommendations were formulated with multiple goals: to restore prestress force lost by damaged tendons, to improve the structure's water-tightness, and to provide strength redundancy to compensate for potential future issues.

Response

Actions taken to address identified concerns were aimed at restoring original design capacity with replacement tendons, providing additional corrosion protection, and removing the source of moisture intrusion. Following the investigations, specific repair actions were taken in multiple spans, including the following:

- For Span 3, tendons that had lost post-tensioning force were replaced.
- Tendons in Spans 1, 2, 4, and 5 with evident wire breaks were exposed, sealed, and entombed in a corrosion protection material. All tendons in these spans were assumed to retain effective post-tensioning force.
- Post-tensioning pour backs were repaired with an epoxy grout.
- A surface seal coat was applied to the interior of the box girder as an additional measure of protection.
- Repaired identified concrete cracking with injections.
- An existing drainage system was permanently sealed at road-level, and drainage pipes inside the structure were removed.

Summary

The Plymouth Avenue Bridge in Minneapolis, Minnesota, underwent routine inspections until 2010, when an inspector noted light penetrating the interior of the box for the bridge's underside (bottom slab of box). Despite reporting routine findings in past inspections, an in-depth inspection revealed that the bridge's drainage system—piping water from the top of the deck and passing through the box—had been the source of moisture intrusion for many years. Remediation actions include tendon replacement to re-achieve original design capacity, re-entombment of exposed tendons, repair of pour backs, crack injection, and removal of the drainage system.

CHAPTER 4

Summary and Conclusions

Concerted efforts to improve the durability of post-tensioned bridges have been made since the technology made it into the concrete bridge industry, yet opportunities for further improvement remain. For some states, existing PT structures continue to require repair and maintenance actions. Often, these are the solutions that bridge owners have formulated after consultation with industry consultants and one key agency—the Florida Department of Transportation. Some states on the other hand, such as Texas and California, have many PT structures in their inventories, but they did not report in their survey response that they had instigated repairs.

Lessons of the current state-of-the-practice can be gathered from the results of a survey of state departments of transportation on their construction, inspection, and repair practices specific to PT structures. Several findings of the survey and case examples are salient:

- A majority of states have PT structures (44).
- The number of PT structures in different states is widely varied, with some states having no or few structures, and others having hundreds.
- Many states (23) have experience with PT repair.
- While many state DOTs are referencing key guidance documents (such as PTI/ASBI M50 and PTI M55) or other states' specifications when developing or updating their own PT specifications, nonuniformity is significant from state to state.
- Consideration of durability during the design phase, through the designation of a protection level, for example, is not widely practiced among state DOTs.
- Issues related to methods of construction remain. Most often, they are related to the process of grout/filler injection and duct pressure testing prior to injection.
- State DOTs continue to have issues with particular materials specific to PT construction, most notably grout filler materials and pour-back materials.
- Several state DOTs have made it a standard practice to make provisions for the installation of tendons in the future to provide redundancy when addressing issues with a PT structure.
- Routine inspections are not sufficient in identifying issues in PT structures before they become severe. As found in several of the case examples, evidence of PT system damage was not identified before the situation became critical. Inspection by persons with PT-specific experience is recommended.
- Recently, states have begun to use materials in novel applications in an effort to improve the corrosion protection of existing structures, including the use of injectable, proprietary corrosion inhibitors and flexible filler materials (such as microcrystalline waxes). Several states have injected proprietary corrosion inhibitors into compromised tendons.

Acronyms and Abbreviations

ACI 318	American Concrete Institute's Building Code Requirements for Structural Concrete
ACI	American Concrete Institute
ASBI	American Segmental Bridge Institute
DOT	Department of Transportation
fib	International Federation for Structural Concrete
FRP	fiber-reinforced polymer
GPR	ground penetrating radar
HDPE	high-density polyethylene
IE	impact echo
IRT	infrared thermography
LDE	low-destructive evaluation
LPR	linear polarization resistance
MFL	magnetic flux leakage
MITT	modified inclined tube test
NBIS	National Bridge Inspection Standards
NDE	nondestructive evaluation
PCI	Precast/Prestressed Concrete Institute
PL	protection level
PT	post-tensioning
PTI	Post-Tensioning Institute
PVC	polyvinyl chloride
RH	relative humidity
SCC	stress corrosion cracking
SIBIE	stack imaging of spectral amplitudes based on impact echo

Glossary

Admixture: A material (usually a liquid or powder) that is a component of cementitious grout and is added immediately before or during mixing.

Aggregate: Granular material, such as sand, gravel, crushed stone, iron blast-furnace slag, or recycled aggregates including crushed hydraulic cement concrete, used with a cementing medium to form concrete or mortar.

Anchor: A steel element either cast into concrete or post-installed into a hardened concrete member and used to transmit applied loads to the concrete. Also called an anchorage.

Anchorage zone: In post-tensioned members, the region of the member through which the concentrated prestressing force is transferred to concrete and distributed more uniformly across the section; its extent is equal to the largest dimension of the cross-section. For anchorage devices located away from the end of a member, the anchorage zone includes the disturbed regions ahead of and behind the anchorage device.

Bleed: The autogenous flow of mixing water within, or its emergence from, freshly placed grout; caused by the settlement of the solid materials within the mass and filtering action of strands, wires, and bars.

Bridge: Any structure spanning not less than 20 ft that forms part of a roadway. In this document, generally part of a highway.

Cementitious materials: Materials having cementing value if used in grout, mortar, or concrete, including portland cement, blended hydraulic cements, expansive cement, fly ash, raw or calcined natural pozzolan, slag cement, and silica fume, but excluding alternative cements.

Connection: Region of a structure that joins two or more members; a connection also refers to a region that joins members, of which one or more is precast.

Duct: Material forming a conduit to accommodate the prestressing steel installation and to provide an annular space for the filler material (i.e., grout or flexible filler), which protects the prestressing steel.

Durability: Ability of a structure or member to resist deterioration that impairs performance or limits service life in the environment for which it was designed.

Flexible filler: Non-cementitious filler material. Its use results in an unbonded tendon, lacking stress-strain compatibility with the primary concrete member. Flexible fillers may include petroleum-derived microcrystalline waxes, greases, or polymer gels.

Grout: A mixture of cementitious materials and water, with or without mineral additives, admixtures, or fine aggregate. In PT applications, it is proportioned to produce a pumpable consistency without segregation of the constituents and injected into the duct after post-tensioning to fill the space around the tendon.

Inlet: Tubing or duct used for injection of grout into the duct.

Joint: Portion of a structure common to intersecting members.

Outlet: Tubing or duct used to allow the escape of air, water, grout, and bleed water from the duct.

Post-tensioning: A method of prestressing in which the tendons are tensioned after the concrete has reached a specified strength.

Prestressing element: The tension element of a post-tensioning tendon, which is elongated and anchored to provide the necessary permanent prestressing force.

Prestressing steel: The steel element of a post-tensioning tendon, which is elongated and anchored to provide the necessary permanent prestressing force.

Quality assurance: Actions taken to ensure that what is being done and what is being provided are in accordance with the specifications and applicable standards.

Quality control: Actions taken by the contractor to provide control over what is being done and what is being provided to ensure that the specifications and applicable standards of good practice for the work are being followed.

Sheathing: General term for the duct material surrounding the prestressing element to provide corrosion protection or conduit for installation.

Span: Distance between supports.

Strand, seven-wire: Strand (most commonly conforming to ASTM A416 in PT applications) consisting of seven wires having a center wire enclosed tightly by six helically placed outer wires with a uniform pitch of not less than 12 and not more than 16 times the nominal diameter of the strand.

Stress corrosion cracking: Brittle cracking process caused by the conjoint action of tensile stress and a corrodent.

Tendon: A single or group of prestressing elements and their anchorage assemblies that impart the prestress force to a structural member or the ground. Also included are ducts, grouting attachments, and grout.

Tendon, bonded: Tendon in which prestressed reinforcement is continuously bonded to the concrete through grouting of ducts embedded within the concrete cross-section.

Tendon, external: A tendon totally or partially external to the member concrete cross-section, or inside a box section, and attached at the anchor device and deviation points.

Tendon, internal: A tendon totally internal to the member concrete cross-section. When filled with cementitious filler material, such as grout, stress-strain compatibility is maintained, and the material of the cross-section is considered entirely homogeneous.

Tendon, unbonded: Tendon in which prestressed reinforcement is prevented from bonding to the concrete. The prestressing force is permanently transferred to the concrete at the tendon ends by the anchorages only.

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APPENDIX

Survey and Survey Results

The appendix is not printed here but can be found at www.TRB.org by searching for "NCHRP Synthesis 562."

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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